Understanding Autonomous Behaviours in Children: An Investigation of Self-Directed Cognitive Control Development

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Abstract

Gaining autonomy is a key aspect of growing up. However, little is known about how children engage cognitive control in an autonomous (or self-directed) fashion to achieve goals. The aim of this dissertation is to better understand the cognitive processes supporting self-directed control development, examining in particular the potentially prominent role of goal identification. In a first study, we disentangle task selection and task execution by adapting the double registration procedure for use with children, and explore whether these processes follow a similar or different developmental trajectory and to what extent they are influenced by task self-directedness regarding performance costs. We show that task selection development lags behind task execution development, task selection yields both mixing and switch costs whilst task execution yields switch costs only, and that both task selection and task execution are affected by task self-directedness. In a second study, we adapt a paradigm widely used in the adult literature to investigate self-directed control, the voluntary task-switching paradigm, and explore task selection development and the contributions of proactive and reactive control to this form of control. Our results indicate both younger and older children struggle with task selection as compared to adults, and that reactive and proactive control may be related to self-directed control. Further, younger children did not struggle to switch tasks, indicating that switching per se is unlikely to be the main source of difficulty for children when engaging cognitive control. In a last study, we specifically target and disentangle context-tracking and task selection by varying the difficulty on each process in two experiments. We find that, although both processes contribute to self-directed control performance, progress with age is mostly associated with improvements in context-tracking. These results are then discussed and leads to the elaboration of a tentative theoretical model of self-directed control development.

Key words: cognitive control development, self-directed control, goal identification, task selection, context-tracking

Lay summary

When growing up as a child, we progressively engage behaviours during activities from being supervised by adults to being on our own. In other words, we are required to become more and more autonomously with age to achieve our goals. This is particularly the case at school where we are increasingly expected to successfully prepare a school exam by deciding by ourselves which relevant course materials have to be studied. To achieve this task, we need to goal-directedly regulate our thoughts and actions in an autonomous manner without. Although, this behaviour may become increasingly critical for academic achievement, little is known about how what are the cognitive processes and how they develop during childhood. Indeed, research on cognitive control development has mainly focused on situations where its engagement is externally driven about the goal to attain. Identifying goals without help is therefore more challenging without external help. The objective of this dissertation is to better understand how goals are identified in such situations and what are the underlying cognitive processes that are subject to age-related progress in self-directed control, in order to propose a theoretical framework to guide future research and the development of training programmes promoting autonomous behaviours during childhood.

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Table of contents

Chapter 1: Introduction

In our daily lives, we constantly engage cognitive control, the goal-directed regulation of thoughts, actions and emotions (Miller & Cohen, 2001), in various contexts to achieve goals, the mental representations of an intention to perform an action, complete a task, or reach a state (Altmann & Trafton, 2002). For instance, when commuting to work, one needs to engage cognitive control if a car crash drastically slows down the traffic in order to be at work on time. More specifically, this situation requires updating and manipulating the new information of a car crash, inhibiting the usual itinerary and switching to a faster one to reach the goal. These actions map onto the three main components of cognitive control according to Miyake et al. (2000) seminal model which are working memory, inhibition, and cognitive flexibility, respectively (see also Friedman & Miyake, 2017).

Cognitive control is also critical for school-work activities, for instance, ignoring sources of distractions and staying on task while working on homework or studying for exams (e.g., watching TV). and its development during childhood is one of the best predictors for later life successes and academic achievement (e.g., Alloway & Alloway, 2010; Moffitt et al., 2011; Samuels, Tournaki, Blackman, & Zilinski, 2016). Cognitive control protracted development is driven by complex changes in the underlying cognitive processes such as a progressive differentiation of its main executive components (Miyake et al., 2000) from middle to late childhood (e.g., Brydges, Fox, Reid, & Anderson, 2014; Wiebe, Espy, & Charak, 2008), or an increasing ability to flexibly engage a reactive mode of control (i.e., engaging cognitive control in the moment it is needed) or a proactive mode of control (engaging cognitive control in anticipation to upcoming demands; Braver, 2012) depending of the situation (e.g., Chatham, Frank, & Munakata, 2009; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier, Martis, Curran, & Munakata, 2015; Lucenet & Blaye, 2014; Niebaum, Chevalier, Guild, & Munakata, 2019) These cognitive changes are also accompanied by important neural changes with an increasingly focal prefrontal activity, and a segregation and integration of fronto-parietal networks (e.g., Chevalier et al., 2015; Durston et al., 2006; Fair et al., 2009)

Given the goal-directed nature of cognitive control, identifying the goal that one has to reach is key to successfully guide behaviour (e.g., on Thursday children will not look at the day 'Monday' on their homework book if they ignore their goal is to do their homework in advance because they will not have the time to do it during the weekend). Indeed, recent research has shown that goal identification is one of the main factors driving cognitive control development and children progressively improve in their ability to identify and achieve goals (Chevalier, 2015). For instance, in the classroom, when the teacher asks a question that children want to answer (i.e., goal), they have to inhibit their wish to be the first to talk (i.e., inappropriate action) and raise their hand to wait for their turn (i.e., appropriate action), but they also might have to keep track of what other children say in order to adapt their answer. While younger children often start talking without raising their hand and need to be externally driven by explicit reminders from the teacher in order to adaptively engage such cognitive control, older children progressively exert cognitive control in a more self-directed fashion with (or without) increasingly subtle reminders from the teacher to raise their hand before talking. Moreover, most of the personal work required to prepare for a school test is less explicitly guided by teachers or parents as children move up across school grades, hence leading to greater demands on what particular course materials to study and when and how to study them.

It is therefore crucial to better understand what are the cognitive processes underlying the development of self-directed control (i.e., when control is engaged without or few external aids) for both theoretical and educational purposes. Indeed, self-directed control remains largely under-researched (for a review, see Barker & Munakata, 2015), as opposed to externally-driven control (i.e., when control engagement is driven by environmental cues; for reviews see Best & Miller, 2010; Wiebe & Karbach, 2017), and its better understanding has the potential to significantly enhance our general theoretical comprehension of cognitive control. Moreover, although externally driven control has been identified to strongly influence school performance (e.g., Fair et al., 2009), self-directed control is also bound to substantially impact children's lives and academic achievement, and perhaps more than externally driven control, as school activities become increasingly self-directed as children move up school grades. Consequently, gaining a better understanding of self-directed control may also help develop more fine-grained training programmes aiming to improve cognitive control engagement during school-learning activities, as so far these programmes have only focused on externally-driven control (for a review, see Kirk, Gray, Riby, & Cornish, 2015).

1 Externally-driven control versus self-directed control: A dissociation or a continuum?

The transition between externally-driven control and self-directed control has been identified as one the major three transitions in cognitive control development (Munakata, Snyder, & Chatham, 2012). The notion of self-directed control, and its dissociation with externally-driven control, relates back to the distinction between ill-structured and well-structured tasks initially proposed by Reitman (1964) who classified problem solving tasks based on the amount of information available regarding three vectors which are the start state, the goal state and the transformation function. Typically, in ill-structured (i.e., self-directed) tasks, these vectors are incompletely specified but completely specified in well-structured (i.e., externally-driven) tasks (see Goel, 1995; Goel & Grafman, 2000). As noted by Goel and Grafman (2000), two planning tasks such as the Tower of Hanoi and preparing lunch for friends are intrinsically different when it comes to their self-directedness. Indeed, the Tower of Hanoi has no self-directedness demand, with a clear start state (i.e., discs in a stack in ascending order of size on rod A), goal state (i.e., discs in a stack in the same ascending order of size on rod C) and a transformation function driven by specific rules (i.e., only one disc can be moved at a time, each move consists of taking the upper disc from one stack to be placed on the top of another stack and no disc can be placed on top of a smaller disc). Conversely, preparing lunch for friends has a high self-directedness demand, with a vague start state (e.g., time needed) and goal state (e.g., excellent or average meal) with a permissive transformation function (e.g., use of fresh or frozen ingredients). Thus, beyond the fact that there is only one way to successfully complete the Tower of Hanoi and several ways to prepare lunch for friends, one of the key distinctions between these two tasks is that individuals are externally-driven about what to do and when to do it when performing the Tower of Hanoi, whereas they are completely free to decide what to do and when to do it when preparing lunch for friends.

At a first glance, externally-driven control and self-directed control may be viewed as two distinct forms of control, as it is the case for reactive control and proactive control (Braver, 2012).

For instance, this dissociation can be illustrated with the difference in nature between deductive tasks (i.e., when rules are explicitly stated) such as in the Dimensional Change Card Test (DCCS; Zelazo, 2006) and inductive tasks (i.e., when rules need to be inferred) such as in the Flexible Item Selection Task (FIST; Jacques & Zelazo, 2001). In DCCS, individuals have to sort bi-dimensional cards (e.g., blue rabbit) according to their colour or their shape based on explicit cues that indicate to which dimension the cards have to be sorted. In contrast, in FIST, individuals have to first select two bi-dimensional cards out of three that match each other (e.g., same colour) before inferring that they have to select two new cards out of three according to the other dimension (e.g., same shape) based on the previous demonstration on how to sort cards by an experimenter. As such, whereas in DCCS individuals are externally-driven by cues, in FIST individuals need to infer the rule of selecting two cards having the same dimension and then switch by selecting the cards that have the same other dimension, thus relying on self-directed control. Interestingly, in children, flexible performance is observed around 4-years-old (Marcovitch, Boseovski, Knapp, & Kane, 2010) while such performance is attained around 5-years-old (Jacques & Zelazo, 2001), suggesting that FIST is more challenging than DCCS and the development of self-directed control lags behind of externally driven control, or in other words that cognitive control engagement is more challenging when it is self-directed than when it is externally driven in childhood.

However, self-directed cognitive tasks actually vary in degrees of self-directedness, especially through the different amount of information provided by the start state, the goal state and the transformation function (Reitman, 1964). Consider for instance the Verbal Fluency task (Troyer, Moscovitch, & Winocur, 1997) and the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948), which are two examples of self-directed tasks. In the Verbal Fluency, individuals have to say as many items from a particular category (e.g., animals) as possible within a minute. To maximise their performance, individuals should use the efficient strategy of grouping their responses into the same semantic subcategory (e.g., animals from the farm: 'pig, chicken, sheep, cow, duck…') and to self-directedly detect when a switch from one subcategory to another is needed and to which subcategory (e.g., from farm animals to zoo animals). In WCST, individuals have to sort cards according to sorting dimensions (colour, forms or number of geometrical figures) that have to be endogenously inferred from external feedback 'correct' or 'incorrect' given by the experimenter. Critically, switching is entirely self-generated and decided by individuals in the Verbal Fluency task whilst it is in part externally driven by feedback from the experimenter in WCST, although children must select on their own which task to perform on each trial. Therefore, the Verbal Fluency is more self-directly demanding than WCST in terms of task selection demands, suggesting the existence of different layers of self-directedness on a continuum ranging from self-directed and externally driven control in which goal identification plays a key role (Munakata et al., 2012; White, Burgess, & Hill, 2009).

2 Role of goal identification in self-directed control

Self-directedness demands vary hand in hand with goal identification demands. Even in situations in which cognitive control is externally-driven, goal identification is key to efficient cognitive control engagement (Broeker et al., 2018; Chevalier, 2015). In particular, goal identification is often achieved through contextual cues (e.g., tapping foot from parents to indicate to turn off the TV) that guide which relevant behaviour to select and engage (Miller & Cohen, 2001). Yet, children have difficulties to process cues and use this information to select the most relevant task in situations where they have to switch between multiple tasks (Chevalier & Blaye, 2009; Chevalier, Huber, Wiebe, & Espy, 2013). They are better at switching tasks after practicing cue identification (Chevalier, Chatham, & Munakata, 2014; Kray, Gaspard, Karbach, & Blaye, 2013) or when cues are easier to process (Chevalier & Blaye, 2009). Cue processing progressively improves with age, resulting in increasingly successful task selection and, more broadly, cognitive control (Chevalier, 2015).

However, goal identification is particularly difficult when cognitive control is self-directed, as there is no external support to drive what to do and when. To date, very little is known about how children engage cognitive control in self-directed situations. Indeed, only a few developmental studies have explored this question, mainly due to the difficulty of design tasks in which control must be engaged in a self-directed manner (Barker & Munakata, 2015). These studies (Barker et al., 2014; Snyder & Munakata, 2010, 2013) have exclusively used the Verbal Fluency task and observed that although younger children spontaneously generate only a couple of items from one sub-category (e.g., cat, dog, rabbit, bird), they generate more items and switch more often between sub-categories when given pre-task reminders (e.g., 'a cat is a pet' or 'a lion is a zoo animal'), that reduce high goal identification demands (i.e., choices between multiple competing subcategories). Therefore, reducing goal identification demands seems critical for successful task performance in young children, perhaps even more so than switching per se. However, it remains unknown how children engage self-directed control in non-linguistic situations as linguistic ability might be a confound with self-directed performance in the Verbal Fluency task (i.e., better performance might be more linked with better linguistic capacities than self-directed capacities per se). Moreover, the Verbal Fluency task offers very little room for experimental manipulations, and therefore appears as a relatively poor tool to explore goal identification processes in self-directed control development. A better tool, as discussed in the next section, is the task-switching paradigm.

3 Assessing self-directed control with task-switching paradigms

Cognitive control has been investigated with a large variety of experimental paradigms that require individuals to inhibit irrelevant goals, update relevant goals in working memory or switch relevant goals. One of the most widely used paradigms to assess cognitive control is the task-switching paradigm (for reviews, see Grange & Houghton, 2014; Koch, Poljac, Müller, & Kiesel, 2018) in which participants are instructed to perform two (or sometimes more) simple tasks, A and B, either in single blocks in which they perform each task separately or in mixed blocks in which they have to switch back and forth between task A and task B, therefore switching between one relevant goal to another. This design allows for the computation of two types of costs, namely mixing and switch costs (Peng, Kirkham, & Mareschal, 2018; Rubin & Meiran, 2005). Mixing costs are computed by contrasting between single-task trials in single blocks and task repetition trials from the mixed block, and index the difficulty of identifying the relevant task when tasks are mixed (or the ability to maintain two tasks and select the relevant one). Switch costs contrast between task repetition trials and task switch trials from the mixed block and index the cost of task-switching per se. Past research has used three main versions of the task-switching paradigm which are the cued task-switching paradigm (when the task-switching rule is externally-driven by environmental cues; Meiran, 1996), the alternating-runs task-switching paradigm (Rogers & Monsell, 1995), and the voluntary task-switching paradigm (VTS; Arrington & Logan, 2004), but only the last two paradigms specifically target self-directed control as they provide no environmental information such as task cues, response feedback or common stimulus features to determine when and what goal to switch to, such as in cued task-switching paradigms.

3.1 Alternating-runs task-switching paradigm

The alternating-runs task-switching paradigm was first introduced by Rogers and Monsell (1995). In this paradigm, individuals are required to perform one task (Task A) twice and then switch to another task (Task B), therefore following a trial by trial sequence such as AA-BB-AA-BB and so forth. Although the initial experiment by Rogers and Monsell (1995) did not use any task cues, in every trial, the target stimulus rotated in a clockwise direction on a 2 by 2 table, and the stimuli from the two top positions referred to Task A and the stimuli from the two bottom positions referred to Task B. As such, individuals could identify the task that had to be performed on each trial based on the location of the stimulus, which acted as an environmental cue that facilitated task selection. Nevertheless, in subsequent studies on adults (e.g., Altmann, 2007; Kray & Lindenberger, 2000; Wylie & Allport, 2000) and the few done on children (Dauvier, Chevalier, & Blaye, 2012; Kray et al., 2013), no such information was provided. This made task selection particularly challenging as participants have to rely on internal cues to select the relevant task on each trial and have to update what is the relevant task in working memory, by keeping track of the current position in the task sequence. Therefore, participants need to memorise and use the information related to the immediately preceding trials (e.g., if Task A has just been performed twice, Task B is now relevant). Comparing performance on the cued task-switching paradigm and the alternating-runs task-switching paradigm, Altmann (2007) reported that switch costs were larger in the latter than in the former paradigm.

In children, Dauvier et al. (2012) observed that most 5-year-olds can successfully update task goals and switch tasks accordingly, although performance decreased across trials due to growing interference from accumulating traces from past trials, suggesting that working memory (alongside with other potential factors, e.g., backward inhibition) underlies updating and maintaining task-related goals, that help the task selection process. In another study using the alternating-runs task-switching paradigm, Kray et al. (2013) compared 8-10 year-olds and 11-13 year-olds and observed that mixing costs were partly greater for the younger age group than for the older age group for reaction times (RTs), although this difference disappeared for accuracy rates, indicating that task selection was harder for younger children than older children. Interestingly, smaller mixing costs were observed for both age groups when children received verbal self-cueing and spatial cue tasks, hence reducing the costs of task selection.

3.2 Voluntary task-switching paradigm

Another paradigm particularly relevant to investigate goal identification, and more particularly one of its main theoretical components, which is task selection in a self-directed situation, is VTS (Arrington & Logan, 2004). This procedure is considered as the gold standard assessment of self-directed control in adults and engages the prefrontal cortex more than other task-switching paradigms (Forstmann, Brass, Koch, & Von Cramon, 2006). VTS requires individuals to self-directedly choose which task to perform between two tasks on each trial, with the instructions to select the tasks equally often and randomly. Yet, similar to other task-switching paradigms (e.g., Meiran, 1996), task performance is worse in task switch trials than in task repetition trials, and therefore switch costs are observed, especially in terms of RTs (for reviews, see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). In addition, as adults are asked to select both tasks equally often in a random order, this should result in an equal number of task repetition and task switch trials. However, they show a repetition bias (i.e., repeating the task they have just done more often than switching to the other task), quantified by a probability of switching, noted *p*(switch), lower than the optimal score of .5 (around .44), indicating that task selection is particularly effortful and difficult (for a review, see Grange & Houghton, 2014). Interestingly, the repetition bias seems to follow a U-shape pattern with age, as adolescents and elderly people show a stronger repetition bias than adults (Butler & Weywadt, 2013; Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012).

Enough time to prepare for the next trial is important to successfully engaging cognitive control, as evidenced by a smaller repetition bias (higher *p*(switch)), when participants are given a longer preparation time before stimulus onset (Arrington & Logan, 2005; Butler, Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck, 2009; Yeung, 2010). Longer preparation times allow adults to select the next task through the representativeness heuristic, which consists of selecting a task after maintaining a sequence of previously performed tasks in working memory and comparing it with an internal concept of randomness before stimulus onset, hence suggesting that a process like context-tracking might be at play in goal identification. Alternatively, the next task to be performed can be selected via the availability heuristic, which consists of selecting after stimulus onset the task that has just been done. Contrary to the representativeness heuristic, the availability heuristic requires no preparation time but leads to more task repetitions (Arrington & Logan, 2005), whereas enough time to prepare favoured the representativeness heuristic over the availability heuristic. Interestingly, these heuristics map onto the distinction between proactive control and reactive control (Braver, 2012), respectively. Concurrent working memory load leads to more task repetitions in VTS (Liefooghe, Demanet, & Vandierendonck, 2010; Weaver & Arrington, 2010), potentially because it impedes the use of proactive control, which strongly relies on working memory capacities (Marklund & Persson, 2012). However, working memory capacities *per se* seem to not be related to task selection (Butler et al., 2011). This indicates that task selection is largely driven by factors that increase demands on top-down processes, such as time preparation.

However, task selection can be also influenced by other factors tapping on bottom-up processes. For instance, when off-setting the onset timing between the presentations of two stimuli in VTS (also referred to as stimulus onset asynchrony), individuals are biased to choose the task associated with the first stimulus that appears (i.e., either a digit for even/odd classification or a letter for consonant/vowel classification; Arrington, 2008). However, this bias is reduced when the preparation time is increased, suggesting that preparation time could buffer against the bottom-up influence of stimulus availability. Stimulus identity also influences task selection as individuals tend to perform the task associated with a particular stimulus at its first experimental exposure during practice trials (Arrington, Weaver, & Pauker, 2010; Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010). These different biases in task selection seem to convey the message that individuals have a preference for minimising effort (see also Arrington & Yates, 2009; Lien & Ruthruff, 2008; Mayr & Bell, 2006), which is consistent with other non-VTS studies on cognitive effort in adults that used different paradigms (e.g., Demand Selection Tasks (DSTs) or Cognitive Effort Discounting (COG-ED)) to show that individuals tend to avoid cognitive demand Kool, McGuire, Rosen, and Botvinick (2010); Westbrook, Kester, and Braver (2013); Westbrook, Lamichhane, and Braver (2019). Although most VTS research has used two tasks with similar difficulty (i.e., magnitude or parity judgements on numbers; Arrington, Reiman, & Weaver, 2014), some other research has varied the difficulty between the two tasks (e.g., Stroop word reading (easy) and colour naming (difficult) tasks), and showed that this variation greatly influences task selection with a tendency to repeat the difficult task more than the easy task (e.g., Liefooghe et al., 2010; Millington, Poljac, & Yeung, 2013; Yeung, 2010). This indicates that it is hard to switch from a difficult task to an easy task whereas it is fairly straightforward to switch from an easy task to a difficult task. According to these authors, this effect is due to between task interference in which participants perform the weaker task activated in working memory (i.e., the harder task) because it is difficult to switch from this task to the task that is strongly activated (i.e., the easier task), leading them to surprisingly perform the weaker and more difficult task. This idea is related to the common interpretation of asymmetrical switch costs in which, when two tasks have unequal difficulty, the cost is greater when switching to the easiest task than when switching to the hardest task (Ellefson, Shapiro, & Chater, 2006).

Furthermore, a variant of VTS is the double registration procedure that temporally disentangles task selection and task execution by using a task selection prompt (e.g., a question mark) preceding the task execution target (Arrington & Logan, 2005). Therefore, individuals make two responses on each trial, first they enter a response just to select the task and then they enter a second response to execute it. The handful of adult studies using the double registration procedure showed that task selection and task execution are distinct process differently affected by individual and contextual factors. For instance, different working memory capacities did not influence *p*(switch) whereas higher working memory capacities led to smaller switch costs RTs (Butler et al., 2011), reward receipt did not influence *p*(switch) but led to faster RTs and more accurate responses (Fröber, Pfister, & Dreisbach, 2019) and larger task selection costs were observed when switching to the more difficult task, whereas greater task execution costs were observed when switching to the easier task (Millington et al., 2013). Some other research has highlighted a more complex relationship between task selection and task execution with higher *p*(switch) associated with smaller task execution switch costs (Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018) and lowerp(switch) associated with greater task execution demands (Orr, Carp, & Weissman, 2012).

Despite extensive research using VTS in adults, VTS has never been used with children whereas it has the potential to shed light on how self-directed control develops across childhood.

4 Aim of the dissertation

The overarching aim of this dissertation will be to identify and understand the cognitive processes that support the development of self-directed control in order to propose a tentative theoretical model of this form of control. Self-directed control is largely under-researched in the developmental literature, with the exception of a handful of studies (Barker et al., 2014; Snyder & Munakata, 2010, 2013), as opposed to externally-driven control (Best & Miller, 2010; Wiebe & Karbach, 2017). A better understanding of self-directed control development and its age-related cognitive processes has the potential to enhance our general comprehension of cognitive control but also allow finer-grained training programme development, aiming to improve its engagement beyond the scope of programmes developed so far as they have only targeted externally-driven control (e.g., Kirk et al., 2015). This can have strong educational implications as similarly to externally-driven control which has been identified to have a major impact on school performance (e.g., Alloway & Alloway, 2010; Lawson & Farah, 2017; Samuels et al., 2016), self-directed control is also bound to substantially impact children's lives and academic achievement, and perhaps more than externally-driven control, as school activities become increasingly self-directed (i.e., relying on autonomous behaviours) as children move up school grades.

Task selection, which is a key sub-process of goal identification, and task execution are two constructs of cognitive control engagement, which have been conceptually and empirically distinguished in adult studies (Fröber et al., 2019; Logan & Gordon, 2001; Millington et al., 2013; Mittelstädt et al., 2018). More specifically, task selection has been identified to drive externally-driven control development (Chevalier, 2015). However, the demands of this component are particularly costly in situations where no external aids are provided, namely in self-directed situations, conferring potentially a greater role of task selection, but not of task execution, in self-directed control. As such, in Chapter 2, I will adapt the double registration procedure (Arrington & Logan, 2005) with children to identify task selection, and not task execution, as the key component on which the demands vary as regards self-directedness, with a higher demand for the former than the latter form of control across childhood. More precisely, task selection should be mastered later in the development under high self-directedness demands than under low self-directedness whereas task execution should be proficient relatively early in development independently of self-directedness demands.

In Chapter 3, I will focus more especially on task selection in self-directed development and to examine how/if this component changes with age. To this aim, the first step will be to develop a child-friendly paradigm that assesses directly task selection, namely VTS, which is the gold standard paradigm targeting task selection in adults (Arrington & Logan, 2004; Arrington et al., 2014). Task selection in VTS is particularly demanding as individuals have to self-directly (i.e., without the help of environmental cues or memorised sequences) select which task to perform between two tasks with the instructions to perform them about equally often and in a random fashion. I will then use VTS with children to investigate the age-related processes associated with task selection in self-directed control development.

First of all, previous adult research has shown that p(switch), the main measure assessing task selection in VTS, increases near to the optimal performance of .5 under longer preparation time suggesting that time is needed for adults to perform well on VTS (Arrington & Logan, 2005; Butler et al., 2011; Butler & Weywadt, 2013; Liefooghe et al., 2009; Yeung, 2010). More specifically, longer preparation time may encourage the use of the representativeness heuristic whereas shorter preparation time may drive the use of the availability heuristic, which map respectively onto the distinction between reactive control and proactive control (Braver, 2012). Indeed, previous developmental research has shown that 5-years-old children essentially use a reactive form of control when engaging cognitive control and progressively engage adaptively either a reactive or a proactive form of control depending on the situation (e.g., Chevalier et al., 2015; Doebel et al., 2017; Niebaum et al., 2019). As such, one might expect younger children to mostly rely on reactive control, and use the availability heuristic, independently of the time preparation duration. Conversely, older children and adults would rely more on reactive control under short time preparation but more on proactive control under long time preparation, and use the representativeness heuristic. As such, *p*(switch) would be overall lower for younger children than other age groups, but this measure would remain the same under short or long time preparations whereas for older children and adults, *p*(switch) would be lower under short time preparation than under long time preparation. This would highlight a critical role of proactive control in task selection in self-directed development.

However, my investigation will not be restricted to *p*(switch) as we suspect that this sole measure may fail to capture all processes of VTS performance, especially in younger children. Indeed, VTS requires participants to perform each task equally often and in a random manner. Strikingly, they can show a *p*(switch) lower than .5, which is meant to indicate that they perform the two task unequally often while in practice they performed them similarly often (e.g., Task A – Task B – Task B – Task B – Task B – Task A – Task A –Task A). Moreover, a p(switch) can be equal to .5 which indicates optimal performance while they actually used a non-random strategy (e.g., Task A – Task A – Task B – Task B – Task A – Task A). As a consequence, to account for all processes involved in VTS, how well the participants perform the two tasks equally often and how well they did so randomly will be also examined alongside with *p*(switch).

In Chapter 4, resulting from this first adaption of VTS in children, I will argue that successful self-directed performance requires two key sub-processes in goal identification which are keeping track of the context and the use of this information to select the appropriate behaviour, respectively context-tracking and task selection. Two studies will be carried out to explore the respective contributions of these two components in self-directed control development. To this aim, in a first study, I will manipulate the contextual information provided in VTS to specifically target context-tracking by manipulating the amount of environmental support and explore to what extent it influences VTS performance. In a second study, I will mostly target task selection by manipulating task (a)symmetry in which participants will perform either two tasks with the same difficulty or two tasks that differ in terms of difficulty as previous research has shown that different task difficulty strongly influences *p*(switch) (e.g., Poljac et al., 2018). Overall, the results of these two studies will allow for a better understanding of the underlying cognitive components involved in goal identification in VTS performance, and also identify whether these two sub-processes contribute equally or not to developmental progress in self-directed control.

Finally, in Chapter 5, I will present the main methodological and conceptual achievements from this dissertation, before discussing results coming from Chapters 2, 3 and 4, and explain how they shed new light on our understanding of self-directed control development, and will propose a tentative model of self-directed control development. I will then provide potential new avenues for developmental research on self-directed control to test this model and explore questions that go beyond the scope of this thesis, in order to better comprehend cognitive control in general and develop potential training programmes to promote self-directed control.

Chapter 2: Dissociating task selection and task execution in self-directed cognitive control development

Background

In this first empirical chapter, I investigated the separability of task selection and task execution in childhood. To do so, I adapted the double registration procedure for use with children to investigate how task selection and task execution are similarly or differently affected by self-directedness demands and whether these two processes follow similar or different developmental trajectories in children aged 4-5 years-old, 7-8 years-old.

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Disentangling the respective contribution of task selection and task execution in self-directed cognitive control development

Abstract

Task selection and task execution are key constructs in cognitive control development. Yet, little is known about how separable they are and how each contributes to task switching performance. Here, 60 4-5, 61 7-8 and 60 10-11-years-olds completed the double registration procedure, which dissociates these two processes. Task selection yielded both mixing and switch costs, especially in younger children, and task execution mostly yielded switch costs at all age, suggesting that task selection is costlier than task execution. Moreover, both task selection and execution varied with task self-directedness (i.e., to what extent the task is driven by external aids) demands. Whereas task selection and task execution are dissociated regarding performance costs, they nevertheless both contribute to self-directed control.

Key words: cognitive control development, double registration procedure, task selection, task execution, self-directed control, self-directedness, mixing costs, switch costs

At school, children need to engage cognitive control – the goal-directed regulation of thoughts and actions – to follow different teaching instructions, raise their hands before talking or take turns in shared activities. To do so efficiently, they must identify what the goal is and what actions should be taken in order to reach it. In other words, they first need to select the relevant task goal or the appropriate actions before executing them. Although both task selection and task execution are involved when cognitive control is engaged, their respective contributions to children's performance, especially the costs associated with task mixing and switching, have ever been disentangled. The current study aimed to temporally separate task selection and task execution (also referred to as task performance), examined how these processes contribute to both task mixing and switching costs, and how they are differentially affected by task self-directedness demands from early to late childhood.

As one of the best predictors of later life success such as academic achievement, income, and health (e.g., Daly, Delaney, Egan, & Baumeister, 2015; Moffitt et al., 2011), childhood cognitive control has attracted growing scientific interest over the last two decades (Best & Miller, 2010; Moriguchi, Chevalier, & Zelazo, 2016). Importantly, the ability to select the relevant tasks or actions (also referred to as goal identification) has emerged as a key process for efficient cognitive control engagement in adults (Broeker et al., 2018). Task selection is also a major force driving the development of cognitive control across childhood (Chevalier, 2015). For instance, when children have to switch between multiple tasks as a function of task cues, they perform better when the demands on task selection are reduced through cues that are easier to process, after practicing cue detection, or by scaffolding task selection strategies (e.g., Chevalier & Blaye, 2009; Chevalier, Chatham, & Munakata, 2014; Kray, Gaspard, Karbach, & Blaye, 2013; Lucenet & Blaye, 2019).

Task selection is conceptually distinct from task execution. Tasks, which refer to the activity of matching stimuli with responses according to specific rules (i.e., color and shape matching or parity and magnitude judgments), may be represented on two different representation levels, a task level in which instructions and rules guide a specific task (task selection) and a parameter level specifying the stimulus-response association leading to task completion (task execution; Logan & Gordon, 2001). This dissociation has been empirically supported in adult task switching studies reporting either weak or no correlation between task selection measures such as the probability of self-directly deciding (i.e., decide freely), to switch tasks (i.e., *p*(switch)) and task execution measures such as the cost associated with the performance drop when individuals need to switch from one task to another (i.e., switch costs; Arrington & Yates, 2009; Butler, Arrington, & Weywadt, 2011; Mayr & Bell, 2006), hence speaking to the separability of these two processes. However, a drawback of these studies is that they do not disentangle task selection from task execution as both processes are simultaneously captured in one response on each trial. As a consequence, it is unclear how these processes contribute (whether similarly or differently) to performance.

In contrast, the double registration procedure disentangles task selection and task execution by using a task selection prompt (e.g., a question mark) preceding the task execution target (Arrington and Logan, 2005). Therefore, individuals make two responses on each trial, first they enter a response just to select the task and then they enter a second response to execute it. The handful of studies using the double registration procedure with adults, did so in the voluntary task switching paradigm, in which participants freely choose which tasks to perform between two, following the general instructions of performing them equally often and in a random manner. They found that task selection and task execution are distinct processes, differently affected by individual and contextual factors. For instance, working memory capacity and reward influence task execution switch costs but not *p*(switch)—an index of task selection in the voluntary task switching paradigm (Butler et al., 2011; Fröber, Pfister, & Dreisbach, 2019). But other research has highlighted a more complex relation between task selection and task execution. That is, higher *p*(switch) is associated with smaller task execution switch costs (Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018). Further, task difficulty differently affects task selection and task execution, with greater task selection switch costs observed when switching to the harder tasks whereas greater task execution switch costs are found when switching to the easier task (Millington, Poljac, & Yeung, 2013). Moreover, consistent with the conflict monitoring model predicting that a task is more highly activated in working memory following the experience of response conflict (e.g., Botvinick, Carter, Braver, Barch, & Cohen, 2001; Brown, Reynolds, & Braver, 2007), previous congruency influences both task selection and task execution, with higher *p*(switch) associated with better task performance after incongruent trials than congruent trials, but contrary to the predictions of this model, previous accuracy affects *p*(switch) but no task performance, with higher *p*(switch) and less (not more) accurate responses after incorrect responses (Orr, Carp, & Weissman, 2012). However, although these studies indicate that task selection and task execution are dissociated, they are nevertheless both sensitive to between-task inference and congruency effects (Millington et al., 2013; Orr et al., 2012), revealing a more complex picture about their relation and potential relatedness.

Of particular interest, it is unknown whether task selection and/or task execution gives rise to greater mixing costs or switch costs. Specifically, mixing costs were not investigated in the studies using the double registration procedure with adults. Yet, mixing costs capture a critical performance drop associated with repeating a task in blocks where it is mixed with another task (i.e., high task uncertainty), relative to repeating a task in a block where the same task is always relevant (i.e., low task uncertainty). Switch costs, as stated previously, correspond to the additional performance drop on trials where participants actually need to switch tasks relative to task repeat trials within mixed-task blocks (Peng, Kirkham, & Mareschal, 2018; Rubin & Meiran, 2005). As task uncertainty, which affects task selection, is high on both switch and repeat trials within mixed blocks, mixing costs may mostly reflect the difficulty of task selection (e.g., Kikumoto & Mayr, 2017). Further, as task uncertainty may be similar on both switch and repeat trials within mixed blocks (at least when both trial types are equally frequent), switch costs may mostly reflect the greater difficulty of task execution when one needs to reorient attention to information that has been previously ignored (e.g., Courtemanche et al., 2019).

Previous developmental investigations of cognitive control have used different task-switching paradigms in which performance indistinctly reflects both task selection and task execution (e.g., Doebel & Zelazo, 2015; Gonthier, Zira, Colé, & Blaye, 2019), but never with the double registration procedure. It is therefore unknown how these two processes develop across childhood and whether their separability holds during childhood as it does during adulthood (Demanet & Liefooghe, 2014; Dignath, Kiesel, & Eder, 2015; Fröber et al., 2019; Millington et al., 2013; Mittelstädt et al., 2018; Orr et al., 2012a; Poljac, Poljac, & Yeung, 2012). Indeed, recent research has shown that task selection becomes easier with age (e.g., Frick, Brandimonte, & Chevalier, 2019), but it is still unclear whether this is also the case for task execution. For instance, different developmental trajectories between task selection and task execution (e.g., if task execution was mastered earlier in the development than task selection) would speak to the separability of the two processes.

Further, the separability of task selection and execution can be complementarily probed by investigating to what extent these two processes are influenced by distinct factors (e.g., Fröber et al., 2019; Millington et al., 2013; Orr et al., 2012; Poljac et al., 2012). One such factor is the self-directedness demand of cognitive control engagement, which ranges from being externally driven (e.g., forced task choices driven by environmental cues on each trial such as in cued task switching paradigm) to being self-directed (e.g., free task choices on each trial with the global instructions to perform each task equally often and randomly such as in the voluntary task switching paradigm). Self-directedness demand affects the difficulty of task selection, as selecting the most appropriate task is especially challenging for children in self-directed situations in which no external aids guide what tasks/actions to perform and when. Indeed, in such contexts, children perform better when strategies reducing task selection demands are prompted before the task (Barker et al., 2014; Snyder & Munakata, 2010, 2013; but for a review, see Barker & Munakata, 2015). In contrast, there is no *a priori* reason to expect self-directedness demand to affect task execution, as the task should similarly difficult to execute once it has been selected (Butler et al., 2011; Fröber et al., 2019; Millington et al., 2013). Alternatively, one may argue that self-directedness demand may still have an indirect influence on task execution through task selection if the difficulty of task execution is dependent on the difficulty of task selection, which would speak for a less dissociable aspect regarding these two processes.

The current study aimed to disentangle the respective contribution of task selection and task execution to childhood cognitive control by investigating (1) how they give rise to mixing and switch costs and (2) whether or not the self-directedness demand affects these processes. To this end, 4-5, 7-8 and 10-11-years-old children completed alternating-runs task switching paradigm in which the double registration procedure was used. The alternating-runs task switching paradigm requires participants to follow a predictable task-rule sequence such as switching on every other trial (e.g., task A, task A, task B, task B, etc.) without external (environmental) cues as the task has to be performed on *n* trial, which therefore taps more self-directed than on externally-driven engagement of control (Rogers & Monsell, 1995). Self-directedness demand was manipulated by either explicitly teaching children the alternating rule (low self-directedness demand) or letting them infer it from feedback (i.e., high self-directedness demand). Indeed, while children can already follow an alternating task rule without external cues relatively efficiently at around 5 years-old (Dauvier, Chevalier, &

Blaye, 2012), inferring a task rule from feedback largely improves from 7 years-old only before reaching an adult-like performance around 10 years of age (e.g., Chelune & Baer, 1986; Rosselli & Ardila, 1993; Shu, Tien, Lung, & Chang, 2000). Consequently, targeting 4-5-, 7-8- and 10-11-year-olds ensured varying levels of rule-inference ability, hence potentially revealing age-related change in how self-directedness may affect task selection and task execution.

We predicted that mixing costs should arise mostly from task selection and switch costs from task execution, as such we should observe greater mixing costs than switch costs for task selection and greater switch costs than mixing costs for task execution. Moreover, if the difficulties of task selection and task execution are independent of each other as previous research has showed that they are separable processes, we predicted that self-directedness demand should affect task selection performance but not task execution performance. Yet, it remained possible that the higher difficulty of task selection due to greater self-directedness demand may indirectly influence task execution. Finally, as self-directedness demand should be especially costly for younger children, we expected its effect on task selection to decrease with age, and more rapidly under low self-directedness demand than high self-directedness demand. The first and third hypotheses were confirmatory whereas the second hypothesis was exploratory.

Methods

Participants

Participants included 60 4- and 5-year-old children (M_{age} = 5.21 years, SD_{age} = .45, range: 4.25 – 5.98, 27 females), 60 7- and 8-year-old children (M_{age} = 7.92 years, SD_{age} = .30, range: 7.40 – 8.42, 26 females) and 60 10- and 11-year-old children (M_{age} = 10.77 years, SD_{age} = .40, range: 10.00 – 11.73, 34 females). Thirteen additional children were excluded from the analysis: eight children due to an experimental error in the program and four children because they fell outside the targeted age range.

All children were tested at school and prior to data collection, a power analysis was conducted with the program GPOWER (Erdfelder, Faul, & Buchner, 1996) which indicated that 180 children was enough to achieve a statistical power of .85 (Cohen, 1988) with a medium effect size of .25 based on previous studies using a similar paradigm to the present study (e.g., Hung, Huang, Tsai, Chang, & Hung, 2016). Therefore, data collection stopped when the sample size for each age group reached at least 60 children, with 30 children in each instruction condition. Informed written consent was obtained from children's parents and all children provided signed assent and received a small age-appropriate prize (e.g., stickers) at the end of the experiment. Children were mostly Caucasian, monolingual and attended the same school, although socio-demographic information was not systematically collected as we did not have specific hypotheses about SES. All children were drawn from the same school catchment area, suggesting similar socio-economic backgrounds. Age and sex did not differ between conditions in any of the age groups (Table 1). The research project and protocol were approved by an Ethics Committee as well as participating schools. Data collection took place between May 2018 and March 2019.

[Insert Table 1 around here]

Material and procedure

All children were tested individually in a 20-minute session in a quiet room at school. They completed a child-friendly alternating-run task-switching paradigm presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA) in which a monkey needed help to clean up his room. Toys needed to be sorted by colour or shape in two corresponding toy chests, the Colour toy chest and the Shape toy chest.

Each trial started with a question mark alongside the two closed toy chests with two response pictures below each toy chest (i.e., a blue and red patch under the Colour toy chest, a car and teddy-bear patch under the Shape toy chest) (Figure 1). The toy chests were constantly visible on the right- and left-hand sides of the monitor but their locations and corresponding response pictures were counter-balanced across participants. After children selected one of the two closed toy chests by pressing one of two keys ('w' and 'i' on a QWERTY keyboard), the question mark was replaced by a happy monkey face if they selected the correct toy chest or a sad monkey face if they selected the incorrect toy chest. Additionally, the selected toy chest opened and the two response pictures under the other toy chest disappeared. After 500 ms, the monkey face was replaced by the target and children had to match this target with one of the response pictures below the selected toy chest (i.e., the 'car' or 'teddy bear' buttons if the Shape toy chest was selected or the 'red or 'blue' buttons if the Colour toy chest was selected) by pressing the corresponding key on the keyboard ('a', 'd', 'j' or 'l'). As such, when children selected a task, whatever this selection was correct or incorrect based on the alternating rule, they had a chance to nevertheless execute it as we wanted to see if the difficulties of task selection were related to task execution. After the response, the target was replaced by an entire yellow banana if both task selection and task execution was correct, half of a yellow banana if only task selection or task execution was correct, or an entire green banana if both task selection chest and task execution was incorrect.

[Insert Figure 1 around here]

All children first completed two single-task blocks in which they consistently filled the Colour toy chest or the Shape toy chest (order counter-balanced). Each single-task block contained 4 practice trials (repeated if more than two errors were committed) followed by 16 test trials. The experimenter helped children on practice trials if necessary but not on test trials. Then, children were told they would fill the two toy chests at the same time and proceeded to the mixed-task blocks. Children were assigned to one of the two experimental conditions. In the rule instruction condition, they were instructed to start with one dimension (counter-balanced across children) and then change dimension on every second trial. This rule was explained as follows: '*Kiki wants you to fill both the Color and Shape toy chests. He wants you to start with the Color toy chest. He also wants you to sort the toys in a specific order: two toys in the Color toy chest, two toys in the Shape toy chest, two toys in the Color toy chest again, two toys in the Shape toy chest again and so on'*. In the no rule instruction condition, they were instructed to start with a specific dimension, but were not told about the alternation between the two dimensions on every second trial, as they had to guess this rule from the feedback. This was explained as follows: '*Kiki wants you to fill both the Color and Shape toy chests. He wants you to start with the Color toy chest. He also wants you to sort the toys in a specific order and it is your job to guess in which toy chest he wants you to sort the toys. Be careful, it will not be always the same toy chest'*. Importantly, in both conditions, children were also instructed that they would have to restart from the start of the sorting rule if they did not select the correct toy chest and/or match correctly the target with the response button. Children completed a familiarization block of six practice trials before performing two mixed blocks of 32 test trials each separated by a short break. During the break, children were reminded of the instructions according to the instruction conditions they were assigned to, and they were told to start the second block with the same dimension than in the first block.

Data analyses

The double registration procedure (Arrington & Logan, 2005) allowed for the distinction between task selection and task execution processes. Accuracy and RTs were separately examined for each process to better isolate the effects of the fixed factors, but also because RTs for task selection and task execution were not comparable because children could prepare in advance their response before prompt onset (for task selection) whereas they could not do so before stimulus onset (for task execution). Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). Log RTs were examined after discarding the first trial of each block, which were neither a task repetition trial nor task switch trial, which resulted in the removal of 4.17% of the total trials. Moreover, for task selection, only correct task selection trials and task selection trials preceded by correct task execution trials were kept, resulting in the removal of 17.91% of the total trials and RTs above 10,000 milliseconds (ms) or 3 standard deviations above the mean for each participant were also removed (1.59% of the total trials). For task execution, a similar trimming procedure was performed with the difference that this time, we kept RTs of correct task execution trials and task execution trials preceded by correct task selection trials, which corresponded to the removal of 17.92% of the total trials. Finally, RTs below 200 ms and above 10,000 ms or 3 standard deviations above the mean for each participant were also removed, which resulted in the removal of 1.72% trials.

Mixed analysis of variances (ANOVAs) were run on accuracy and log RTs to examine the effect of age group (4-5 year-olds, 7-8 year-olds and 10-11 year-olds) as a between-subjects variable, and instruction condition (rule instruction, no rule instruction), and trial type (single task, task repetition, task switch) as within subject variables. When appropriate and evidenced by Mauchly's tests (Mauchly, 1940), the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Tukey's post hoc tests were used for pairwise comparisons resulting from these anovas when there were multiplicities issues. These analyses were performed on R version 3.6.3 (R Core Team, 2020) using *afex* and *emmeans* packages (Lenth, 2020; Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020). Mixing costs were examined by contrasting trials in single-task blocks (simply referred to as single trials below) with task repetition trials in mixed-task blocks (referred to as task repetition trials), while switch costs were examined by contrasting task repetition trials and task switch trials within mixed-task blocks (Rubin & Meiran, 2005). Rank-based methods with the Holm adjustment (Holm, 1979) to control for type I error (i.e., known as a false positive finding or conclusion) were used for multiple comparisons of costs with the *nparcomp* package (Konietschke, Placzek, Schaarschmidt, & Hothorn, 2015) and more specifically with the *gao_cs* function (Gao, Alvo, Chen, & Li, 2008).

Results

Task selection accuracy

Task selection accuracy was significantly affected by age group, $F(2, 174) = 14.98$, $p < .001$, $\eta^2_p = .15$, instruction condition, $F(1, 174) = 63.30$, $p < .001$, $\eta^2_p = .27$, and trial type, $F(2, 348) = 244.97$, $p < .001$, $\eta^2_p = .58$. As illustrated in Figure 2, overall, 4-5 and 7-8-year-olds did not differ, $p = .079$, but these two age groups were significantly less accurate than 10-11 year-old children ($M_{\text{4-5 year-olds}} = .86$ *vs.* $M_{\text{7-8 year-olds}} = .89$ *vs.* $M_{\text{10-11 year-olds}} = .93$; $ps < .004$). Accuracy was significantly higher with than without rule instruction ($M_{\text{rule instruction condition}} = .94$ *vs.* $M_{\text{no rule instruction condition}} = .85$; $p < .001$) and decreased significantly across single, task repetition, and task switch trials ($M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .86$ *vs.* $M_{\text{task switch trials}} = .82$; $ps < .001$), hence revealing significant mixing and switch costs overall.

Age group and instruction condition significantly interacted, $F(2, 174) = 3.07$, $p = .049$, $\eta^2_p = .03$, 4-5 year-olds were less accurate than 7-8 year-olds and 10-11 year-olds in the rule instruction condition ($M_{\text{4-5 year-olds}} = .89$ *vs.* $M_{\text{7-8 year-olds}} = .95$ *vs.* $M_{\text{10-11 year-olds}} = .96$; $ps < .007$), with no difference between the latter age groups, $p = .694$. Conversely, in the no rule instruction condition, both 4-5 year-olds and 7-8 year-olds showed similar accuracy rates that were significantly lower accurate than 10-11 year-olds ($M_{\text{4-5 year-olds}}$ = .83 *vs.* $M_{\text{7-8 year-olds}}$ = .83 *vs.* $M_{\text{10-11 year-olds}}$ = .90; *ps* < .001).

Age group also interacted with trial type, $F(4, 348) = 15.97$, $p < .001$, $\eta^2_p = .15$. There were significant mixing costs for all ages and significant switch costs for 7-8 year-olds and 10-11 year-olds, but not for 4-5 year-olds for whom non-significant reversed switch costs were observed (4-5 year-olds: $M_{\text{single trials}}$ = 1 *vs.* $M_{\text{task repetition trials}}$ = .78 *vs.* $M_{\text{task switch trials}}$ = .81; 7-8 year-olds: $M_{\text{single trials}}$ = 1 *vs.* $M_{\text{task repetition trials}}$ = .88 *vs.* $M_{\text{task switch trials}}$ = .79; 10-11 year-olds: $M_{\text{single trials}}$ = 1 *vs.* $M_{\text{task repetition trials}}$ = .92 *vs.* $M_{\text{task switch trials}}$ = .87; *ps* < .009 and *p* = .168). Specifically targeting performance costs, we observed that mixing costs were overall significantly higher than switch costs ($M_{\text{mixing costs}}$ = .14 *vs.* $M_{\text{switch costs}}$ = .03; *p* < .001). However, this difference was significant for 4-5 year-olds only ($M_{\text{mixing costs}}$ = .22 *vs.* $M_{\text{switch costs}}$ = -.03; *p* < .001), but not for older children, *ps* > .093. Moreover, 4-5 year-olds showed greater mixing costs than older children ($M_{\text{7-8 year-olds}}$ = .12 and $M_{\text{10-11 year-olds}}$ = .08; *p* < .001), whereas the latter did not differ, *p* = .125. Conversely, higher switch costs were observed for 7-8 year-olds and 10-11 year-olds ($M_{\text{7-8 year-olds}}$ = .08 and $M_{\text{10-11 year-olds}}$ = .04; *ps* < .032) than for 4-5 year-olds.

Finally, instruction condition and trial type significantly interacted, $F(2, 348) = 48.20$, $p < .001$, $\eta^2_p = .22$, with significant mixing costs in both instruction conditions but significant switch costs only in the no rule instruction condition (rule instruction condition: $M_{\text{single trials}}$ = 1 *vs.* $M_{\text{task repetition trials}}$ = .90 *vs.* $M_{\text{task switch trials}}$ = .91; no rule instruction condition: $M_{\text{single trials}}$ = 1 *vs.* $M_{\text{task repetition trials}}$ = .82 *vs.* $M_{\text{task switch trials}}$ = .74; *ps* < 001 and *p* = .868). Mixing costs were higher than switch costs in both instruction conditions (rule instruction condition: $M_{\text{mixing costs}}$ = .10 *vs.* $M_{\text{switch costs}}$ = -.01; no rule instruction condition: $M_{\text{mixing costs}}$ = .18 *vs.* $M_{\text{switch costs}}$ = .07; *ps* < .001). Finally, mixing and switch costs were higher in the no rule instruction condition than in the rule instruction condition, *ps* < .001.

The three-way interaction between age group, instruction condition and trial type failed to reach significance, $p = .061$.

[Insert Figure 2 around here]

Task selection RTs

On task selection RTs, there were main effects of age, $F(2, 169) = 138.48$, $p < .001$, $\eta^2_p = .62$, trial type, $F(2, 338) = 30.14$, $p < .001$, $\eta^2_p = .26$, but not of instruction condition, $p = .252$ (Figure 3). Overall, task selection RTs decreased across all three age groups ($M_{\text{4-5 year-olds}} = 7.27$ log-transformed ms (ln ms) *vs.* $M_{\text{7-8 year-olds}} = 6.67$ ln ms *vs.* $M_{\text{10-11 year-olds}} = 6.13$ ln ms; $ps < .001$), and from single task trials to task repetition trials, and from the latter trials to task switch trials ($M_{\text{single task trials}} = 6.57$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.65$ ln ms *vs.* $M_{\text{task switch trials}} = 6.80$ ln ms; $ps < .019$), revealing significant mixing and switch costs. But mixing and switch costs did not differ from each other, $p = .283$.

A two-way interaction between age group and trial type, $F(4, 338) = 10.65$, $p < .001$, $\eta^2_p = .11$, further revealed that switch costs were significant for 4-5 year-olds only ($M_{\text{task repetition trials}} = 7.13$ ln ms *vs.* $M_{\text{task switch trials}} = 7.56$ ms; $p < 001$. Switch costs were significantly higher than mixing costs for 4-5 year-olds ($M_{\text{mixing costs}} = .01$ *vs.* $M_{\text{switch costs}} = .43$; $p < .001$), whereas no differences between these costs were observed for older children, $ps > .277$. 4-5 year-olds showed greater switch costs than older children ($M_{\text{7-8 year-olds}} = .02$ and $M_{\text{10-11 year-olds}} = .00$; $ps < .001$), whereas these costs between the two latter age groups did not differ, $p = 1$. Mixing costs did not vary across age groups, $ps > .474$.

Instruction condition also interacted with trial type, $F(2, 338) = 4.51$, $p = .014$, $\eta^2_p = .03$. Significant mixing and switch costs were observed in the no rule instruction condition ($M_{\text{single task trials}} = 6.54$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.72$ ln ms *vs.* $M_{\text{task switch trials}} = 6.85$ ln ms; $ps < .004$), but only significant switch costs were observed in the rule instruction condition

($M_{\text{single task trials}}$ = 6.59 ln ms *vs.* $M_{\text{task repetition trials}}$ = 6.59 ln ms *vs.* $M_{\text{task switch trials}}$ = 6.75 ln ms; $p < .001$). Mixing and switch costs did not differ between the instruction conditions, *ps* > .070.

[Insert Figure 3 around here]

Task execution accuracy

Age group and trial type significantly affected task execution accuracy, $F(2, 174) = 15.91$, $p < .001$, $\eta^2_p = .15$ and $F(2, 348) = 14.83$, $p < .001$, $\eta^2_p = .08$, but not instruction condition, $p = .514$, and none of these factors interacted with each other, *ps* > .171 (Figure 4). Overall, 4-5 year-olds were less accurate than 7-8 year-olds and 10-11 year-olds, but the latter two did not differ from each other ($M_{\text{4-5 year-olds}}$ = .89 *vs.* $M_{\text{7-8 year-olds}}$ = .93 *vs.* $M_{\text{10-11 year-olds}}$ = .94; *p*s < .001 and $p = .391$). Accuracy was lower in both single trials and task repetition trials, which did not differ from each other, relative to switch trials ($M_{\text{single trials}}$ = .92 *vs.* $M_{\text{task repetition trials}}$ = .91 *vs.* $M_{\text{task switch trials}}$ = .94; $p = .508$ and $p < .001$), hence revealing no significant mixing costs and reverse switch costs.

[Insert Figure 4 around here]

Task execution RTs

On task execution RTs, there were main effects of age group, $F(2, 169) = 197.70$, $p < .001$, $\eta^2_p = .70$, and trial type, $F(2, 332) = 378.99$, $p < .001$, $\eta^2_p = .69$, but not of instruction condition, $p = .834$. As illustrated in Figure 5, RTs significantly decreased with age ($M_{\text{4-5 year-olds}}$ = 7.48 ln ms *vs.* $M_{\text{7-8 year-olds}}$ = 7.08 ln ms *vs.* $M_{\text{10-11 year-olds}}$ = 6.67 ln ms; *p*s < .001), and were faster on single trials than on task repetition trials, and on task repetition trials than on task switch trials ($M_{\text{single trials}}$ = .6.88 ln ms *vs.* $M_{\text{task repetition trials}}$ = 7.02 ln ms *vs.* $M_{\text{task switch trials}}$ = 7.30 ln ms; *ps* < .001), hence revealing significant mixing and switch costs. Switch costs were significantly higher than mixing costs overall ($M_{\text{mixing costs}}$ = .13 ln ms *vs.* $M_{\text{switch costs}}$ = .28 ln ms; $p < .001$).

Moreover, age group significantly interacted with trial type, $F(4, 338) = 3.10$, $p = .020$, $\eta^2_p = .03$. Mixing costs were significant for 4-5 year-olds and 7-8 year-olds (4-5 years-old: $M_{\text{single task trials}} = 7.26$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.43$ ln ms; 7-8 years-old: $M_{\text{single task trials}} = 6.90$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.02$ ln ms; $ps < .024$), but not for 10-11 year-olds, $p = .059$. Switch costs were significant for all age groups (4-5 years-old: $M_{\text{single task trials}} = 7.26$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.43$ ln ms *vs.* $M_{\text{task switch trials}} = 7.75$ ln ms; 7-8 years-old: $M_{\text{single task trials}} = 6.90$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.02$ ln ms *vs.* $M_{\text{task switch trials}} = 7.31$ ln ms; 10-11 years-old: $M_{\text{single task trials}} = 6.52$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.62$ ln ms *vs.* $M_{\text{task switch trials}} = 6.87$ ln ms; $ps < .001$). Switch costs were significantly higher than mixing costs for all age group (4-5 year-olds: $M_{\text{mixing costs}} = .18$ ln ms *vs.* $M_{\text{switch costs}} = .31$ ln ms; 7-8 year-olds: $M_{\text{mixing costs}} = .12$ ln ms *vs.* $M_{\text{switch costs}} = .29$ ln ms; 10-11 year-olds: $M_{\text{mixing costs}} = .10$ ln ms *vs.* $M_{\text{switch costs}} = .25$ ln ms; $ps < .013$). Mixing and switch costs did not differ between age groups, $ps > .280$.

Finally, instruction condition significantly interacted with trial type, $F(2, 338) = 3.61$, $p = .030$, $\eta^2_p = .03$. Mixing and switch costs were significant in both instruction conditions (rule instruction condition: $M_{\text{single task trials}} = 6.89$ ln ms *vs* $M_{\text{task repetition trials}} = 6.99$ ln ms *vs.* $M_{\text{task switch trials}} = 7.32$ ln ms; no rule instruction condition: $M_{\text{single task trials}} = 6.87$ ln ms *vs* $M_{\text{task repetition trials}} = 7.04$ ln ms *vs.* $M_{\text{task switch trials}} = 7.29$ ln ms; $ps < .001$). Switch costs were higher than mixing costs in both instruction conditions, although this difference was smaller in the no rule instruction condition (rule instruction condition: $M_{\text{mixing costs}} = .09$ ln ms *vs.* $M_{\text{switch costs}} = .32$ ms ls; no rule instruction condition: $M_{\text{mixing costs}} = .17$ ln ms *vs.* $M_{\text{switch costs}} = .25$ ln ms; respectively $p = .007$ and $p = .017$). Mixing costs were higher in the no rule instruction condition than in the rule instruction condition whereas switch costs were higher in the rule instruction condition than in the no rule instruction condition, $ps < .016$.

[Insert Figure 5 around here]

Discussion

The present study temporally separated task selection and task execution to investigate to what extent these processes lead to mixing and switch costs and are affected by the self-directedness demand during childhood. Although mixing costs and switch costs were observed for both processes, task selection gave rise to both mixing and switch costs whereas task execution mostly gave rise to switch costs. Further, the self-directedness demand affected both task selection and task execution. This suggests that although these two processes are relatively independent regarding performance costs with age, they neverthless both contribute to self-directed cognitive control development.

One of the main finding is that task selection was associated with both mixing and switch costs whereas task execution was mostly associated with switch costs. This pattern is not consistent with the proposal that mixing costs mostly reflect task selection and switch costs task execution, but it nevertheless indicates that performance costs are differently associated with these processes, hence speaking for their relative dissociation. However, whereas greater switch costs than mixing costs were observed in task execution RTs for all age groups, these costs differently contributed to task selection with age. Indeed, task selection accuracy mixing costs were significantly greater than task selection switch costs for 4-5 year-olds but were similar for 7-8 year-olds and 10-11 year-olds. This primilarly sugests that mixing costs are more associated with task selection at a young age whereas both mixing and switch costs contribute to this this process in older children.

However, when it came to RTs, task selection switch costs were higher than task selection mixing costs for RTs in 4-5 years-old children, whereas once again no difference was observed between these costs for older children. Thus, identifying when to switch the task was costlier for 4-5 year-olds than for other age groups (see Chevalier, Huber, Wiebe, & Espy, 2013). Interestingly, younger children showed non-significant reversed switch costs for task selection accuracy. This pattern suggests a speed-accuracy trade-off: 4-5 year-olds may have been especially cautious on switch trials, leading to longer but more accurate responses on these trials as compared to task repetition trials, hence the reversed or small switch costs at that age. One possible interpretation for this trade-off is that 4-5 year-olds were easily detected that they needed to switch tasks, but figuring out which task to switch to and/or activating this task in working memory, was especially time consuming for them as compared to older children, potentially because of lower working memory capacities (Camos & Barrouillet, 2018). Similarly, we found similar reversed switch costs for task execution accuracy associated with longer switch costs for task execution RTs for all age groups. This pattern is consistent with potential speed-accuracy trade-offs: taking longer to executive a task seems to ensure greater likelihood of success.

Taken together, these findings on task selection suggest that although both mixing and switch contribute to this process; these costs were higher in 4-5 year-olds than older children, indicating that this process was particularly costly for young children. This potentially shed new light on why children under 7-8 years-old struggle with task selection (Frick et al., 2019; Munakata, Snyder, & Chatham, 2012; Snyder & Munakata, 2010, 2013). Conversely, on task execution, switch costs were greater than mixing costs at all ages and these costs did not differ between age groups, indicating that this pattern is steady across childhood. Besides speaking for the separability of these two processes, the fact that task selection was associated with both performance costs whereas task execution was mostly associated with switch costs seem to indicate that task execution is less costly and master earlier in the development.

Furthemore, there were no significant costs for task execution accuracy, suggesting that task execution was less difficult to achieve than task selection in our paradigm. However, a limitation of this finding is that mixing costs may not have been observed for task execution accuracy because of the specificity of the paradigm used in the current study. Indeed, once the task was selected, only that task remained available for task execution. This procedure is different from what has been done in some adult studies in which response options related to both tasks remained available during task execution (e.g., Demanet & Liefooghe, 2014). Children may have made less errors because they could only perform the task they previously selected, hence reducing accuracy mixing costs. Note however that significant mixing and switch costs were observed for task execution RTs, suggesting that executing the selected task remained demanding even though our setup likely resulted in highly successful outcomes, hence revealing that the difficulties of task selection did influence the difficulties of task execution.

This transfer of difficulty from task selection to task execution was more salient when the self-directedness demand varied as both processes were affected. More specifically, both mixing costs for task selection accuracy and task execution RTs were significantly higher in the no rule instruction condition than in the rule instruction condition. Therefore, the costs associated to the selection of the relevant task when the two tasks are mixed, and more precisely when the relevant task has to be self-inferred, requiring increasingly working memory capacities and efficient abstract representations (Camos & Barrouillet, 2018; Munakata et al., 2012), transferred to when this task has to be executed. As such, although task selection and task execution processes progressively dissociate from each other with age, they are both sensitive to high self-directedness demand (i.e., when control engagement is especially self-directed). This has important implications for our understanding of the supposedly separability of these two processes as shown in the adult literature (e.g., Butler et al., 2011; Fröber et al., 2019; Millington et al., 2013; Mittelstädt et al., 2018; Orr et al., 2012). Indeed, while these studies have shown that factors such as between-task interference or previous congruency both affect task selection and task execution, but in a different ways (see Millington et al., 2013; Orr, Carp, & Weissman, 2012), our study reports that these processes are similarly influenced by self-directedness demand, suggesting their dissociable but relatedness on this aspect and that they both contribute to self-directed control development as this effect hold for all age groups.

Note that consistent with our initial hypothesis, task selection accuracy significantly increased from 4-5 years-old to 7-8 years-old, while no difference was observed between 7-8 and 10-11 years-old under low self-directedness demand. Conversely, both 4-5 and 7-8 years-old were significantly less accurate than 10-11 years-old under high self-directedness demand. These findings are in line with Dauvier et al. (2012) who showed that children from 5-6 years-olds can be successful when the task provides alternating rule instructions even without external cues. In contrast, inferring the rule from feedback was challenging for children below 7-8 years-olds (e.g., Chelune & Baer, 1986; Rosselli & Ardila, 1993; Shu et al., 2000). However, this finding does not necessarily mean that children below 7-8 years of age cannot use feedback to infer a rule to guide behaviours. For instance, 4- to 6-years-olds children can successfully infer the relevant tasks based on feedback and switch between task sets, although not as efficiently as older children and adults (e.g., Chevalier, Dauvier, & Blaye, 2009; Cianchetti, Corona, Foscoliano, Contu, & Sannio-Fancello, 2007; Jacques & Zelazo, 2001). But, here, children assigned to the no rule instruction condition did not only need to infer the relevant task, they had to infer a relevant sequence of tasks. This required them to maintain the information conveyed by the feedback but also the information about the tasks they performed over multiple trials before they could actually infer the alternating rule. As such, it was more demanding in terms of working memory and abstract reasoning that what children are asked to do in tasks where after one or two trials children can know which task is now relevant for several further trials once they have inferred the newly relevant task (e.g., Chevalier et al., 2009; Cianchetti et al., 2007; Jacques & Zelazo, 2001). Therefore, improvement in task selection in our paradigm may be linked to increasingly working memory capacities and efficient abstract representations with age (Camos & Barrouillet, 2018; Munakata et al., 2012).

Our study is limited by a potential confound between the self-directedness demand and reinforcement induced in our paradigm. As the task was easier to select with rule instructions, children in this condition received more positive feedback than children in the no rule instruction condition. Importantly, more frequently getting positive feedback may increase positive affect in the rule instruction condition. Research has shown that positive phasic (i.e., inducing an emotion before each trial) and tonic (i.e., inducing a general mood in the long run) affect reducing switch costs (e.g., Liu & Wang, 2014; Müller et al., 2007; Wang, Chen, & Yue, 2017; but for a review, see Goschke & Bolte, 2014). To further investigate this potential confound related to affect and motivation, we conducted further analyses on RTs for task execution to control for the phasic and tonic affect (see Supplemental Material). In short, we found the exact same pattern of findings as in the main analyses, suggesting that switch costs were more related to task execution than mixing costs. Moreover, if phasic and tonic affect had an effect on our initial results, we should have observed greater switch costs in the no rule instruction condition than in the rule instruction condition. However, in our initial analyses and supplemental analyses, we observed that switch costs were greater in the rule instruction condition than in the no rule instruction condition for task execution RTs. This indicates that children who received more negative feedback (in the no rule instruction condition) did not show a more pronounced switch costs that children who received more positive feedback (in the rule instruction condition), but the reverse, and that phasic and tonic affect did not influence this result.

Finally, another limitation relates to the fact that although no precise socioeconomic status (SES) information regarding the children tested in this study was collected, they all came from private schools and therefore our sample was largely homogenous. As such, our results require cautious as they might not be generalizable to the larger population. Indeed, lower SES has been found to be associated with poorer cognitive control in situations where cognitive control is externally driven (Halse, Steinsbekk, Hammar, Belsky, & Wichstrøm, 2019; Lawson, Hook, & Farah, 2018). In contrast, little is known about the influence of SES on self-directed engagement of cognitive control during childhood. Consequently, future research on self-directed control should examine how it may be influenced by SES, especially given that self-directed control likely plays a critical role in children's lives and academic achievement.

To conclude, our findings speak to the separability of task selection and task execution regarding performance costs. Indeed, both mixing and switch costs contributed to task selection, but to a greater extent in younger children than in older children, whereas task execution is mostly associated with switch costs at all age. This suggests that task execution and its underlying mechanism is mastered earlier in the development than task selection. One venue for future research is to explore how different modes of control engagement can account for this difference. For instance, younger children may show both greater performance costs for task selection because they rely more on a reactive form of control whereas older children engage more flexibly a proactive form of control, which potentially reduces these costs more than mixing costs, in task selection. However, so far this assumption remains speculative. Moreover, self-directedness demand variations have a greater effect on mixing costs than on switch costs, especially when this demand is high. But this effect can be seen in both task selection and task execution, suggesting that the difficulties in task selection transfers to some extent to task execution, and therefore that these two processes are related on this aspect. Consequently, although these two processes appear to be dissociated with age regarding performance costs, they are related when it comes to self-directedness, suggesting that these two processes should be targeted if one wants to promote self-directed control development, which is key fostering autonomy in children.

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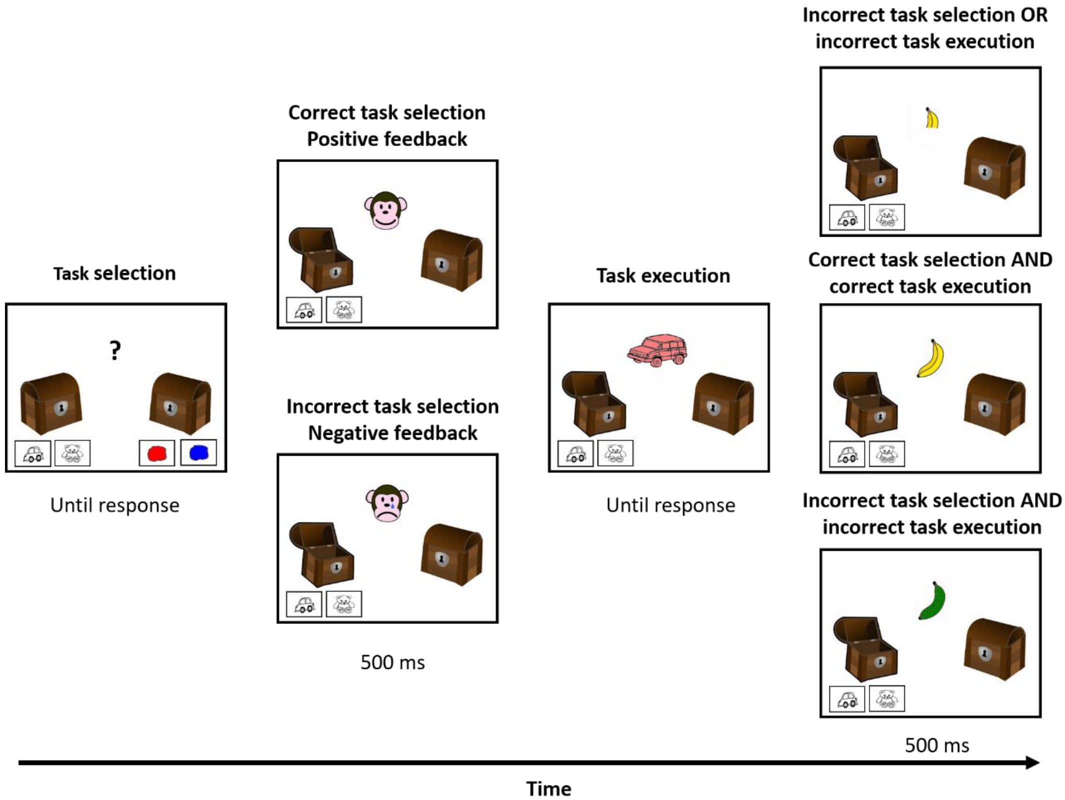

Figure 1: Double registration procedure in the child-friendly alternating-run task-switching paradigm. Children had to first select one of the two toy chests between the Color and Shape toy chests and then matched the toys with the appropriate response picture below the toy chest.

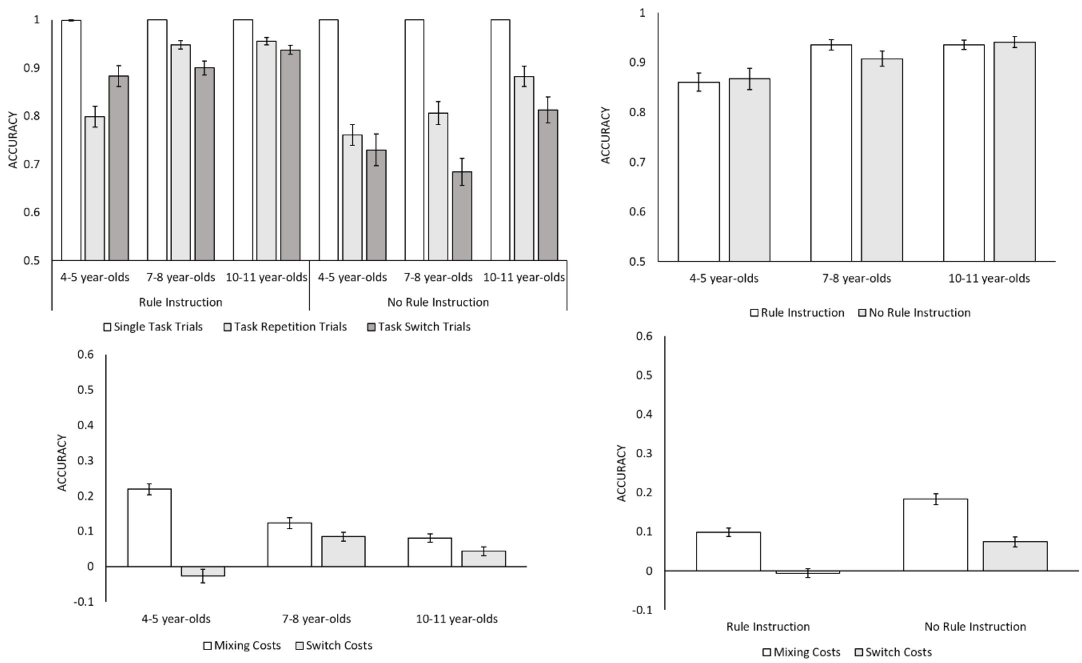

Figure 2: Accuracy for trial type (single task trials, task repetition trials, task switch trials; top left figure) as a function of age group (4-5 year-olds, 7-8 year-olds, 10-11 year-olds) and instruction condition (rule instruction, no rule instruction), as a function of age group and instruction condition all trials confounded (top right figure), as a function of costs (mixing costs, switch costs) and age group (bottom left figure) and as a function of costs and instruction condition (bottom right figure). Error bars represent standard errors.

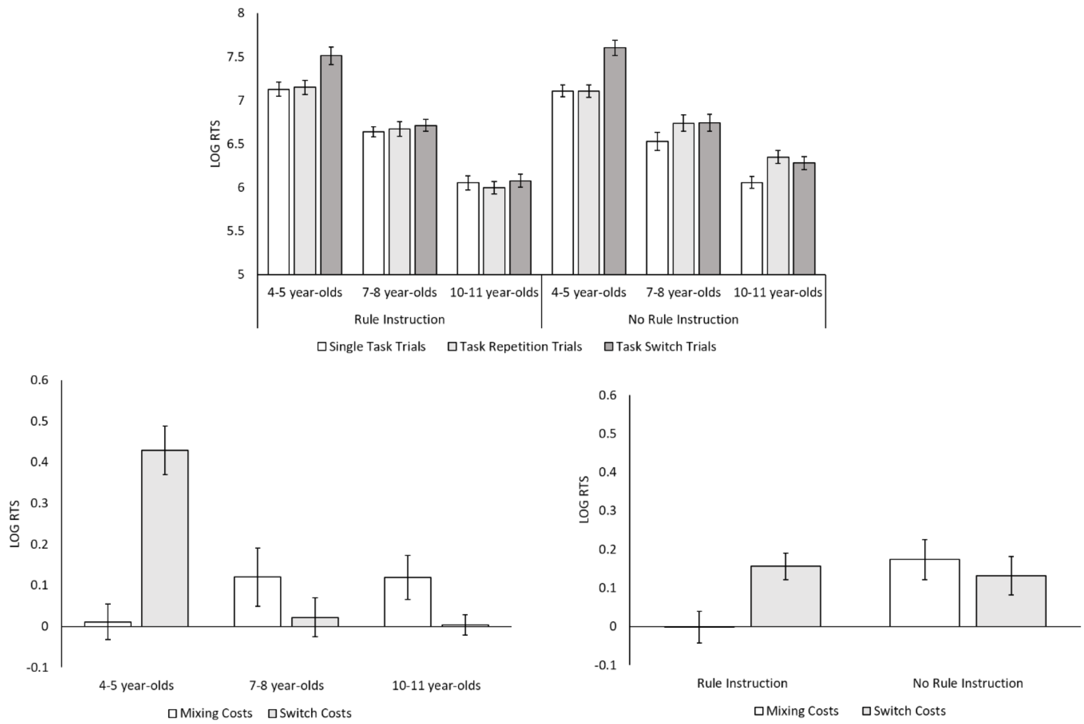

Figure 3: Log RTs for trial type (single task trials, task repetition trials, task switch trials) as a function of age group (4-5 year-olds, 7-8 year-olds, 10-11 year-olds) and instruction condition (rule instruction, no rule instruction; top left figure), as a function of costs (mixing costs, switch costs) and age group (top right figure) and as a function of costs and instruction condition (bottom figure). Error bars represent standard errors.

Figure 4: Accuracy for trial type (single task trials, task repetition trials, task switch trials) as a function of age group (4-5 year-olds, 7-8 year-olds, 10-11 year-olds and instruction condition (rule instruction, no rule instruction). Error bars represent standard errors. 4-5 year-olds were less accurate than other age groups.

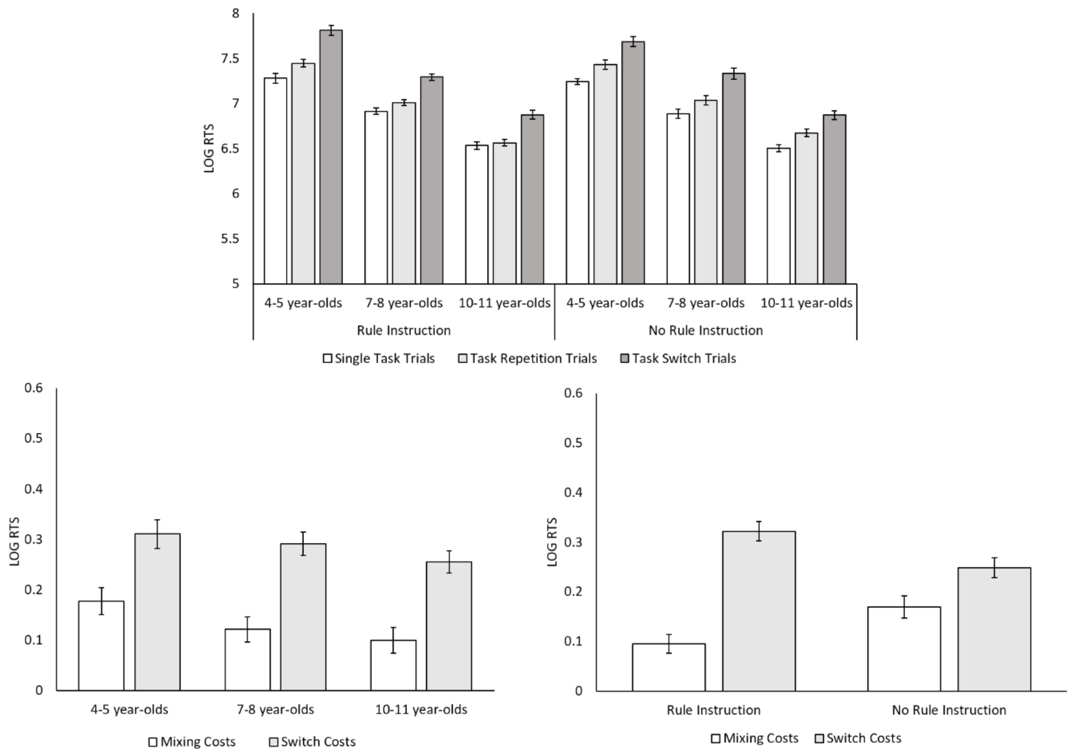

Figure 5: Log RTs for trial type (single task trials, task repetition trials, task switch trials) as a function of age group (4-5 year-olds, 7-8 year-olds, 10-11 year-olds) and instruction condition (rule instruction, no rule instruction; top left figure) and as a function of costs (mixing costs, switch costs) and age group (top right figure) and as a function of costs and instruction condition. Error bars represent standard errors.

Table 1: Sample size, age mean, age deviation, age range and sex ratio as a function of age group and condition.

Age Groups	**Condition**	***N***	**M_{age}, SD_{age}**	***P*-value (M_{age}) t-test**	**Age range**	**Sex ratio**	***P*-value (Sex ratio) χ2**
4-5 year-olds	Rule	30	5.13, .48	.164	4.25 – 5.98	19M, 11F	.194
	No rule	30	5.29, .40		4.37 – 5.94	14M, 16F	
7-8 year-olds	Rule	30	7.85, .29	.067	7.40 – 8.42	17M, 13F	1
	No rule	30	7.99, .31		7.45 – 8.40	17M, 13F	
10-11 year-olds	Rule	30	10.70, .37	.194	10.00 – 11.29	14M, 16F	.602
	No rule	30	10.84, .42		10.10 – 11.73	12M, 18F	

Supplemental Material

Analyses controlling for feedback contingency differences between conditions on task execution RTs

Data Analyses

Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). RTs were examined after discarding the first trial of each block, which were neither a task repetition trial nor task switch trial, which resulted in the removal of 4.17% of the total trials. Then, to eliminate the potential confound between the instruction condition (rule instruction vs. no-instruction) and feedback received (positive vs. negative), and more specifically, confound of phasic affect, we kept trials when children started to correctly implement the rule in the mixed-blocks. That is, only trials that followed four correct trials for task selection and three correct trials for task execution in a row (e.g., colour-colour-shape-shape) were examined as they indicated that children learned the alternating rule. This was the case as children in the no-rule condition instruction received about the same number of positive feedback on task selection than children in the rule instruction condition ($M_{\text{rule instruction condition}}$ = 85.53% *vs.* $M_{\text{no-rule instruction condition}}$ = 90.63%, W = 2709, p = .151), and this similarity hold for all age groups, ps > .239. This trimming procedure removed 18.11% of the total trials. For task execution, we kept RTs of correct task execution trials and task execution trials preceded by correct task selection trials, which corresponded to the removal of 10.87% of the total trials. Finally, RTs below 200 ms and above 10,000 ms or 3 standard deviations above the mean for each participant were also removed, which resulted in the removal of 1.32% trials.

Mixed analysis of variances (ANOVAs) were run on log-transformed RTs to examine the effect of age group (4-5 year-olds, 7-8 year-olds and 10-11 year-olds) as a between subjects variable, and instruction condition (rule instruction, no rule instruction), and trial type (single, task repetition, task switch) as within subject variables. We used the total number of feedback received in single-task blocks and trials from the mixed-blocks in total as a covariate to control for the potential confound of tonic affect (i.e. reward history). We also add the number of trials after the rule has been implemented as this number was higher in the rule instruction condition than in the no-rule instruction condition. When appropriate and evidenced by Mauchly's tests (Mauchly, 1940), the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Tukey's post hoc tests were used for pairwise comparisons resulting from these anovas. These analyses were performed on R version 3.6.3 (R Core Team, 2020) using *afex* and *emmeans* packages for computing anovas and running pairwise comparisons with Tukey adjustments when there were multiplicity issues (Lenth, 2020; Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020). Mixing costs were examined by contrasting trials in single-task blocks (simply referred to as single trials below) with task repetition trials in mixed-task blocks (referred to as task repetition trials), while switch costs were examined by contrasting task repetition trials and task switch trials within mixed-task blocks (Rubin & Meiran, 2005). Rank-based non-parametric methods with the Holm-Bonferroni adjustment to control for error type I (Holm, 1979) were used for multiple comparisons of costs with the *nparcomp* package (Konietschke, Placzek, Schaarschmidt, & Hothorn, 2015) and the function 'gao_cs' (Gao, Alvo, Chen, & Li, 2008).

Results

Task execution RTs

On task execution RTs, there were main effects of age group, $F(2, 151) = 137.90$, $p < .001$, $\eta^2_p = .65$, and trial type, $F(2, 302) = 3.46$, $p = .036$, $\eta^2_p = .02$, but not of instruction condition and number of feedback and number of trials, $p > .835$ (Figure 2). Overall, task execution RTs significantly decreased across age groups ($M_{4\text{-}5\ \text{year-olds}} = 7.49$ ln ms *vs.* $M_{7\text{-}8}$

year-olds = 7.06 ln ms *vs.* $M_{\text{10-11 year-olds}}$ = 6.67 ln ms; *ps* < .001), and were faster on single trials than on task repetition trials and on task repetition trials than on task switch trials ($M_{\text{single trials}}$ = .6.87 ln ms *vs.* $M_{\text{task repetition trials}}$ = 6.99 ln ms *vs.* $M_{\text{task switch trials}}$ = 7.28 ln ms; *ps* < .001), hence revealing significant mixing and switch costs. Switch costs were significantly higher than mixing costs ($M_{\text{mixing costs}}$ = .12 *vs.* $M_{\text{switch costs}}$ = .29; $p < .001$), and this held for all age groups (4-5 year-olds: $M_{\text{mixing costs}}$ = .15 vs. $M_{\text{switch costs}}$ = .36; 7-8 year-olds: $M_{\text{mixing costs}}$ = .10 vs. $M_{\text{switch costs}}$ = .28; 10-11 year-olds: $M_{\text{mixing costs}}$ = .11 *vs.* $M_{\text{switch costs}}$ = .24; *ps* < .002).

Trial type significantly interacted with instruction condition, $F(2, 302) = 3.17$, p = .047, $\eta^2_p = .02$. Mixing and switch costs were significant in both instruction conditions (rule instruction condition: $M_{\text{single trials}}$ = 6.90 ln ms vs. $M_{\text{task repetition trials}}$ = 6.99 ln ms vs. $M_{\text{task switch trials}}$ = 7.32 ln ms; no rule instruction condition: $M_{\text{single trials}}$ = 6.83 ln ms vs. $M_{\text{task repetition trials}}$ ln ms vs. $M_{\text{task switch}}$ = 7.23 ln ms; ps < .001). Although mixing costs were greater in the no-rule instruction condition than in the rule instruction condition, this was not significant, $p = .052$, whereas switch costs were significantly higher in the rule instruction condition than in the no-rule instruction condition ($M_{\text{rule instruction condition}}$ = .33 vs. $M_{\text{no rule instruction condition}}$ = .24; $p = .004$). Finally, switch costs were larger than mixing costs in the instruction condition ($M_{\text{mixing costs}}$ = .09 vs. $M_{\text{switch costs}}$ = .33; $p < .001$), but it failed to reach significance in the no instruction condition, $p = .052$.

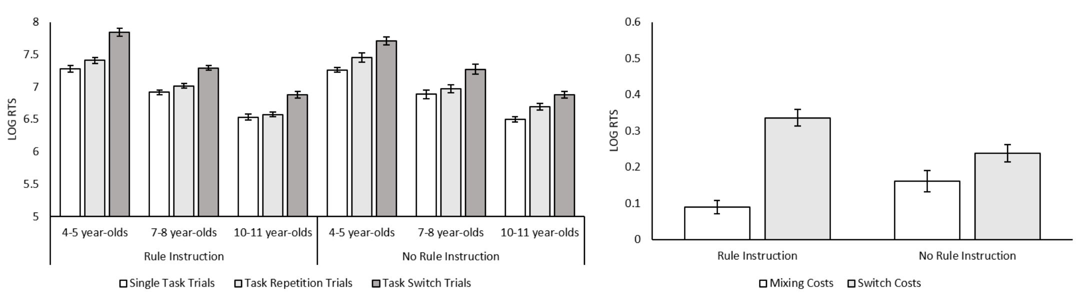

Figure 2. Log RTs for trial type (single task trials, task repetition trials, task switch trials) as a function of age group (4-5 year-olds, 7-8 year-olds, 10-11 year-olds) and instruction

condition (rule instruction, no rule instruction; left figure) and costs (mixing costs, switch costs) as a function of instruction condition (right figure). Error bars represent standard errors.

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Chapter 3: Investigating task selection in self-directed cognitive control development using the voluntary task-switching paradigm

Background

In this second empirical chapter, I investigated goal identification, with a particular focus on task selection, in childhood. To do so, I adapted the voluntary task-switching paradigm for use with children as young as 5 years-old, and looked at two other indices than *p*(switch), which were task balance and task randomness. I also investigated the role of reactive and proactive control by manipulating the preparation time before stimulus onset.

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Voluntary Task Switching in Children: Switching More Reduces the Cost of Task Selection

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Emerging cognitive control supports increasingly efficient goal-directed behaviors. With age, children are increasingly expected to decide autonomously and with little external aid which goals to attain. However, little is known about how children engage cognitive control in such a self-directed fashion. The present study examined self-directed control development by adapting the voluntary task switching paradigm—the gold standard measure of this control form in adults—for use with 5–6-year-old and 9–10-year-old children. Overall, *p*(switch) suggested that even younger children can engage self-directed control successfully. However, other measures showed they struggled with task selection. Specifically, compared with older children and adults, they relied more on systematic strategies which reduced the cost of task selection, even when the strategy involved switching more often. Like externally driven control, self-directed control relies critically on task selection processes. These two forms of control likely form a continuum rather than two discrete categories.

Keywords: self-directed control, cognitive control, voluntary task switching, endogenous control, cognitive development

Gaining autonomy is a key aspect of growing up. As children grow older, they are increasingly expected to behave autonomously with little or no aids regarding what to do, how to do it, and when to do it. For instance, most of the personal work required to prepare for a school test is less explicitly guided by teachers or parents as children move up across school grades, hence leading to greater demands on what particular course materials to study and when and how to study them. To complete such tasks, children engage cognitive control to regulate their thoughts and actions in a self-directed manner. Although self-directed control engagement is bound to substantially impact on children's lives, including academic achievement, little is known about its development. So far, cognitive control development has been studied almost exclusively in situations where its engagement is externally driven by cues, reminders, or clear instructions about the goal to attain. In contrast, the current study examined how children self-directedly engage control when no external support is provided.

Even in situations in which cognitive control is externally driven, the ability to select the relevant tasks or actions to perform (or identify goals to pursue) is key to efficient cognitive control (Broeker et al., 2018) and its development across childhood (Chevalier, 2015). In particular, task selection (goal identification) is often inferred through cues that guide relevant behavior selection and engagement (Miller & Cohen, 2001). Indeed, frontoparietal activation while engaging cognitive control is largely related to cue processing in adolescents and adults (Chatham et al., 2012; Church, Bunge, Petersen, & Schlaggar, 2017). Yet, children struggle to process cues and use this info to select the most relevant task in situations where they have to switch between multiple tasks (Chevalier & Blaye, 2009; Chevalier, Huber, Wiebe, & Espy, 2013). They are better at switching tasks after practicing cue detection (Chevalier, Chatham, & Munakata, 2014; Kray, Gaspard, Karbach, & Blaye, 2013) or when cues are easier to process (Chevalier & Blaye, 2009). Cue processing progressively improves with age, resulting in increasingly successful task selection and, more broadly, cognitive control (Chevalier, 2015). As task selection is central, even in situations in which cognitive control is externally driven, children may particularly struggle when cognitive control is self-directed, as there is no external support to drive what to do and when.

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To date, however, very little is known about how children engage cognitive control in self-directed situations, as only a handful of developmental studies have explored this question, probably because of the difficulty of running less controlled tasks in which control must be engaged in a self-directed manner (Barker & Munakata, 2015). These studies have essentially used the semantic verbal fluency task (Troyer, Moscovitch, & Winocur, 1997), in which children must name as many items from a specific category (e.g., animals) as they can (Barker et al., 2014; Snyder & Munakata, 2010, 2013). Although younger children spontaneously generate only a couple of items from one subcategory (e.g., cat, dog, rabbit, bird), they generate more items and switch more often between subcategories when given pretask reminders (e.g., "a cat is a pet" or "a lion is a zoo animal") that reduce high task selection demands (i.e., choices between multiple competing subcategories; Snyder & Munakata, 2010, 2013). Therefore, reducing task selection demands seems critical for successful task performance in young children, perhaps even more so than switching per se. However, it remains unknown how children engage self-directed control in nonlinguistic situations, what task selection strategies they use to achieve a goal and how this use of strategies changes with age, and to what extent becoming increasingly self-directed may relate to adaptive use of different control modes. These questions may not be easily answered using the verbal fluency task as this task leaves little room for experimental manipulations (Isacoff & Stromswold, 2014).

A promising paradigm to chart out the development of self-directed control is the voluntary task switching (VTS; Arrington & Logan, 2004) procedure, which is considered as the gold standard assessment of self-directed control in adults (for a review, see Arrington, Reiman, & Weaver, 2014). Unlike other externally driven task switching paradigms, VTS requires individuals to freely choose which task to perform between two simple tasks on each trial, with the constraints to select the tasks equally often and in a random fashion. But, similar to other task switching paradigms (e.g., Meiran, 1996), task performance is worse in task switch trials than in task repetition trials, and therefore a switch cost is observed, especially in terms of reaction times (RTs, for review, see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). In addition, adults are asked to choose both tasks equally often in a random order, which should result in an equal number of task repetitions and task switches. They nevertheless show a robust repetition bias (i.e., repeating the task they have just done more often than switching to the other task), quantified by a probability of switching [noted *p*(switch) and ranging from 0 to 1] lower than the optimal score of .5 (around .44), indicating that task selection is particularly effortful (e.g., Arrington & Logan, 2005; Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018). Interestingly, the repetition bias seems to follow a U-shaped pattern with age, as adolescents and elderly people show a stronger repetition bias than adults (Butler & Weywadt, 2013; Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012). In line with these findings, VTS performance is associated with greater frontal and prefrontal activation than cued task switching (in which the relevant task on each trial is externally signaled by a task cue). Specifically, enhanced activation in the rostral and dorsal anterior cingulate cortex may reflect voluntary control of action and free choice between competitive alternatives (Demanet, De Baene, Arrington, & Brass, 2013; Marsh, Blair, Vythilingam, Busis, & Blair, 2007), while activation in the posterior cingulate may support self-chosen intentions (Soon, He, Bode, & Haynes, 2013). Thus, due to higher task selection demands, VTS is more demanding than other task switching paradigms.

Having enough time to prepare for the next trial is crucial to engage the cognitive control processes needed to select and execute a task, as evidenced by a smaller repetition bias and higher *p*(switch) when participants are given a longer preparation time (i.e., response to stimulus interval) before stimulus onset (Arrington & Logan, 2005; Butler, Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck, 2009; Yeung, 2010). Adults may benefit from longer preparation time because they need time to adaptively select the task they want to perform next through the representativeness heuristic, that is, selecting a task after maintaining a sequence of recently performed tasks in working memory and comparing it with an internal sequence of randomness before stimulus onset. Alternatively, the task to be performed next can be selected via the availability heuristic, which consists in selecting after stimulus onset the task that has just been done, which has had less time to decay in working memory and is thus easier to reactivate than the other task. Unlike the representativeness heuristic, the availability heuristic requires no preparation time to operate but it leads to more task repetitions (Arrington & Logan, 2005). Long preparation times may allow adults to anticipate and prepare in advance for the upcoming task, hence encouraging the representativeness heuristic over the availability heuristic. Interestingly, these two heuristics map onto the distinction between proactive control (i.e., engagement of control in anticipation of upcoming demands) and reactive control (i.e., engagement of control in the moment it is needed; Braver, 2012), respectively. Concurrent working memory load leads to more task repetitions in VTS (Liefooghe, Demanet, & Vandierendonck, 2010; Weaver & Arrington, 2010), perhaps because it prevents proactive control, which heavily relies on working memory for the sustained maintenance of goal-relevant information (Marklund & Persson, 2012). Unlike adults and older children, younger children tend to be biased toward reactive control, rarely engaging proactive control (Chevalier, Martis, Curran, & Munakata, 2015; Doebel et al., 2017; Munakata, Snyder, & Chatham, 2012). They may therefore rely more on the availability than the representativeness heuristic in VTS, and thus show a greater repetition bias than adults, even with long preparation times.

However, the repetition bias or *p*(switch), which is the unique measure of task selection processes in most prior studies in adults, may fail to capture important aspects of VTS performance, such as the need to perform both tasks equally often and in random fashion. Specifically, a participant could show a *p*(switch) equal to .5, which is considered as a perfect score of randomness, but nevertheless use a nonrandom strategy such as systematically switching every two trials (e.g., Task A, Task A, Task B, Task B, Task A, Task A, etc.). Indeed, there are individual differences in self-organized strategies in VTS, with a majority of adults adaptively engaging in both task repetitions and task switches (i.e., alternators), but also a minority using more basic nonrandom strategies such as constantly switching between the tasks (i.e., switchers) or constantly repeating the task they have just done on a previous trial (i.e., blockers; Reissland & Manzey, 2016). This heterogeneity in the use of strategies in VTS echoes developmental research showing great heterogeneity regarding the use of strategies in externally driven task switching situations in children (e.g., Blakey, Visser, & Carroll, 2016; Dauvier, Chevalier, & Blaye, 2012). Consequently, a full account of task selection processes involved in VTS should at least report measures of (a) task transition, assessing how often participants repeat or switch tasks; (b) task selection equality, indexing how well they perform the two (or more) tasks equally often; and (c) task randomness, indicating how often participants use nonrandom strategies.

VTS has never been used with children, despite its prominent role in the adult literature and potential to shed light on self-directed control development. The present study adapted this paradigm for children to investigate age-related changes in task selection processes when no external aid is provided. We targeted 5- to 6- and 9- to 10-year-olds (in addition to adults), given the now well-established transition from reactive to proactive control during that age range (Chevalier et al., 2015; Munakata et al., 2012). We used three different measures to comprehensively capture three main aspects of task selection processes: (a) task transition through *p*(switch), (b) task selection equality through the relative difference between the proportion of trials in which each of the two tasks was selected, and (c) task randomness through occurrences of nonrandom strategies. In addition, we examined the role of reactive and proactive control in VTS by varying preparation time duration using short (600 ms) and long (2,000 ms) preparation times. Given that younger children engage proactive control less than adults, we expected them to show a lower *p*(switch) and to be worse at performing the two tasks equally often and be less sensitive to preparation time variations than other age groups, who should show a higher *p*(switch) and perform the two tasks more equally often especially with the longer preparation time. Importantly, we expected younger children to struggle particularly with task selection and therefore rely more on nonrandom strategies than older children and adults.

Method

Participants

Participants included twenty-nine 5- and 6-year-old children (M_{age} = 6.11 years, SD_{age} = .45, range: 5.33–6.71, 14 females), 31 9- and 10-year-old children (M_{age} = 10.05 years, SD_{age} = .52, range: 9.13–10.95, 13 females), and 31 adults (M_{age} = 21.80 years, SD_{age} = 3.36, range: 18.77–30.77, 15 females). Two additional 5–6-year-olds were excluded, because one failed the practice (see the Method section) the other fell outside the targeted age range. Data collection stopped when the sample size of each age group reached 31 participants, which is comparable to prior developmental studies comparing 5- and 6-year-old children and 9- and 10-year-old children (e.g., Chevalier, Jackson, Revueltas Roux, Moriguchi, & Auyeung, 2019) or to adult studies using VTS (e.g., Fröber, Pfister, & Dreisbach, 2019). Children were recruited from one private preschool and one private primary school and adults were all students enrolling at the University of Edinburgh. Informed written consent was obtained from children's parents and from adult participants and all children provided signed assent. Children received a small age-appropriate prize (e.g., stickers) and adults received either course credits or £5 for their participation. The research project and protocols were approved by the Ethics Committee from the University of Edinburgh (Study title: "Role of preparation time in voluntary task switching in children and adults": Ref. no. 23–1718/2,) as well as all participating schools.

Material and Procedure

All participants were tested individually in a 30-min session either in a quiet room at school (children) or in the laboratory (adults). They completed a child-friendly, VTS paradigm adapted from a similar paradigm in adults (Arrington & Logan, 2004) and presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). It was introduced to participants as "Santa Claus and Mitch the Bad Elf Game." Participants were instructed to help Santa sorting toys into two bags for Christmas, while watching out for Mitch, an elf toy thief. Participants were instructed to switch voluntarily between sorting bidimensional targets (e.g., a blue teddy) by color and shape. If they played the color game, they had to place the target in the color bag by pressing the response box button matching the target's color, whereas they had to place the target in the shape bag if they played the shape game, by pressing the button matching the matching the target's shape. Participants were given two additional instructions (modeled after Arrington & Logan, 2004), corresponding to two main features of the adult version of VTS. First, participants had to put roughly as many toys in each of the two bags. Second, they had to play the two tasks randomly, which was conveyed by asking participants to make sure Mitch could not predict how they would sort the toys. Otherwise, Mitch would show up and steal the toy inside the present box (the now empty present box would still be moved into the selected bag).

Each trial started with a central fixation cross alongside the two bags with two responses pictures below each bag (i.e., a blue and red patch under the color bag, a car and teddy bear under the shape bag; Figure 1). The bags were constantly visible on the right- and left-hand sides of the monitor but the locations of the bags and responses pictures were counterbalanced across participants. After 1,500 ms (in the long preparation time condition) or 100 ms (in the short preparation time condition), the fixation cross disappeared and was replaced with the target that remained on the screen until a response was entered by pressing one of the four buttons on a response box. After the response, the target was replaced by a closed present box that remained at the center of the screen for 250 ms before being moved to the selected bag for 250 ms. If a predictable strategy was used and detected by the program (for details on the different strategies implemented in the program and how many trials in a row of a particular strategy would trigger Mitch the thief elf, see the Data Processing and Analysis subsection), the target was replaced by an opened present box with a small version of the toy alongside Mitch the thief elf for 250 ms and the sound effect "ah-ah." Then the same present box was closed and moved into the bag chosen by the participants while the small version of the toy and Mitch remained on the screen for 250 ms. Whether or not the elf showed up, the present box inside the bag was no longer visible during the following trial.

All participants completed the task in two conditions (order counterbalanced across participants). In the short preparation time condition, the fixation cross was visible only for 100 ms, leaving a total of 600 ms (cross fixation duration = 100 ms + present moving or Mitch appearing duration = 500 ms) for the participant

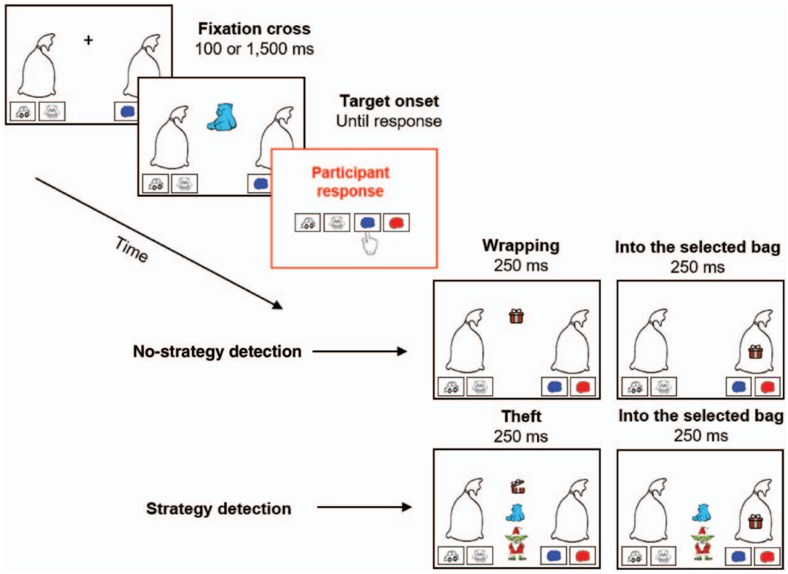

Figure 1. Child-friendly voluntary task switching paradigm. Participants had to decide whether to sort the toys in the color or shape bags according to the general instructions of filling the two bags with about the same number of toys in a no-predictable fashion to avoid the theft of the toys. See the online article for the color version of this figure.

to prepare for the upcoming trial. In contrast, in the long preparation time condition, the fixation cross was visible for 1,500 ms, providing a total of 2,000 ms (cross fixation duration = 1,500 ms + present moving or Mitch appearing duration = 500 ms) for the participant to prepare for the upcoming trial. Different combinations of colors and shapes were used in each condition (either car-teddy-blue-red or doll-plane-green-pink).

In both conditions, participants first completed two single blocks in which they were instructed to always sort toys by either color or shape, in order to get familiar with each task. Each single block comprised four warm-up trials (repeated up to 2 times if participants made more than 2 errors) followed by 16 test trials. The order of the color and shape-matching tasks was counterbalanced across participants. Participants then completed two mixed blocks in which they were instructed to switch voluntarily between the two tasks with the two constraints of filling the two bags equally often and tricking Mitch as much as they could. To make sure all participants understood the instructions, the experimenter performed two demonstration trials. In the first demonstration, participants observed the experimenter alternate systematically between the two bags (i.e., two tasks) on seven trials ("color-shape-color-shape-color-shape-color" or "shape-color-shape-color-shape-color-shape" with order counterbalanced across participants and conditions), which resulted in the last target being stolen by Mitch. In the second demonstration, participants were shown one of two potential ways of successfully sorting the toys ("color-color-shape-color-shape-shape-shape-color-color-shape-color-color" or "shape-shape-color-shape-color-color-color-shape-shape-color-shape-shape" with order counterbalanced across participants and conditions), putting the same number of toys into each bag and avoiding the theft of toys by Mitch. Participants then completed 16 practice trials. Practice trials were repeated (maximum 3 times) if one bag contained more than 10 toys (62.5%), Mitch stole a toy (i.e., detection of a predictable strategy), or more than eight errors (50%) were made. Critically, participants first performed the practice trials on their own but if these trials needed to be repeated, they received help from the experimenter. Participants who failed to pass the practice trials after three repetitions were excluded (n = 1). Participants then completed two mixed-task blocks of 40 test trials separated by a short break. At the end of each mixed block (practice trials and test trials), feedback was provided to encourage participants to respond accurately and follow the instructions of preforming the two tasks equally often and in a random fashion. Feedback conveyed the number of errors, whether one bag contained more toys than the other (more than 62.5% of the toys), and the number of toys stolen by Mitch. Although no feedback regarding response times was given, participants were instructed to respond as quickly as possible before each block.

Data Processing and Analysis

Trial type was determined as follows: if the task (color or shape) performed on trial n repeated from the trial n-1, this trial was coded as a "task repetition" trial, if, conversely, the task on trial n was different from trial n-1, this trial was coded as a "task switch" trial. Task performance, task choice and task transition measures, and the use of strategies were analyzed. Task performance was indexed by mean accuracy and RTs for each trial type (single, task repetition, and task switch), which allowed estimating mixing costs (contrasting between single trials and task repetition trials) and switch costs (contrasting between task repetition trials and task switch trials. Mixing costs index the difficulty of selecting the relevant task when tasks are mixed and switch costs index the difficulty of switching from one task to another per se. These analyses were performed after discarding the first trial of each block. Moreover, RTs were log-transformed (to correct for skewness and minimize baseline differences between age groups although only raw values are reported for the sake of clarity) and only RTs for correct responses immediately preceded by another correct response were kept in the analyses, resulting in the removal of 13.46% of the trials in total (a rate in line with previous studies using VTS in adults, e.g., Arrington & Weaver, 2015). RTs on trials following the appearance of the bad elf were also removed as their latencies were longer than on normal trials, which represented 1.07% of the remaining trials. Finally, RTs were trimmed out if they were under 200 ms, to account for accidental button presses, or greater than 3 standard deviations above the mean of each participant (computed separately for trials from single blocks, and repeat and switch trials from mixed blocks) or 10,000 ms, resulting in the removal of 1.69% of the remaining trials.

Task selection was measured via three indices. (a) Task transition was calculated based on whether the task was repeated or switched on a given trial *n*. This measure, often considered as the main outcome variable in VTS studies, corresponding to *p*(switch), and was calculated by dividing the number of task switch trials by the total number of task switch and task repetition trials (i.e., 78). This score ranged between 0 and 1 with 5 corresponding to a perfectly equal number of task repetitions and task switches. (b) Task selection equality corresponded to a task selection measure of the ability to perform each task equally often in the mixed blocks. This index consisted in the relative difference between the proportion of trials in which the shape bag was selected and the proportion of trials in which the color bag was selected. As such, the closer this index was to 0, the more equally frequently the two tasks were performed. (c) Task randomness was via occurrences of 10 different systematic strategies. These strategies ranged from five basic to complex patterns as follows:

Repetition only (detected over 7 trials):

- Task A, Task A, Task A, Task A, Task A, Task A, Task A.
- Task B, Task B, Task B, Task B, Task B, Task B, Task B.

Switch only (detected over 7 trials):

- Task A, Task B, Task A, Task B, Task A, Task B, Task A.
- Task B, Task A, Task B, Task A, Task B, Task A, Task B.

One repetition and switch (detected over 9 trials):

- Task A, Task A, Task B, Task B, Task A, Task A, Task B, Task B, Task A.
- Task B, Task B, Task A, Task A, Task B, Task B, Task A, Task A, Task B.

Two repetitions and switch (detected over 11 trials):

- Task A, Task A, Task A, Task B, Task B, Task B, Task A, Task A, Task A, Task B, Task B.
- Task B, Task B, Task B, Task A, Task A, Task A, Task B, Task B, Task B, Task A, Task A.

Three repetitions and switch (detected over 13 trials):

- Task A, Task A, Task A, Task A, Task B, Task B, Task B, Task B, Task A, Task A, Task A, Task A, Task B.
- Task B, Task B, Task B, Task B, Task A, Task A, Task A, Task A, Task B, Task B, Task B, Task B, Task A.

If participants used one of these patterns, the corresponding strategy was automatically detected by the program and triggered Mitch the thief elf. The number of time these strategies was used during the game (i.e., when Mitch showed up) provided an indication of randomness. Moreover, our analyses also focused on the qualitative type of strategies (e.g., simple repetition of one task for seven trials or more complex alternation with a switch every third repetition for 13 trials).

Task performance and task selection measures were analyzed with mixed analyses of variance (ANOVAs) with age as a between-subjects variable, and preparation time and/or trial type as within-subject variables, Bonferroni-corrected post hoc tests, and *t* tests. When appropriate, the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Finally, the type of strategies used across age groups and/or without preparation time durations was analyzed with multivariate analyses of covariance (MANOVAs).

Results

Task Performance

Accuracy rates. A 3 (age group: 5–6 years, 9–10 years, adults) × 2 (preparation time: short, long) × 3 (trial type: single, task repetition, task switch) mixed ANOVA was performed on accuracy rates. The analysis showed main effects of age, $F(2, 88) = 10.56$, $p < .001$, $\eta_p^2 = .19$, trial type, $F(2, 176) = 3.80$, $p = .038$, $\eta_p^2 = .04$, and preparation time, $F(1, 88) = 8.68$, $p = .004$, $\eta_p^2 = .09$, and these effects were qualified by a significant two-way interaction between age and preparation time, $F(2, 88) = 4.30$, $p = .017$, $\eta_p^2 = .09$, and a significant three-way interaction, $F(4, 176) = 3.57$, $p = .014$, $\eta_p^2 = .07$. Preparation time differentially affected trial type across age groups (Figure 2). More specifically, while 5–6-year-olds were significantly less accurate with the short

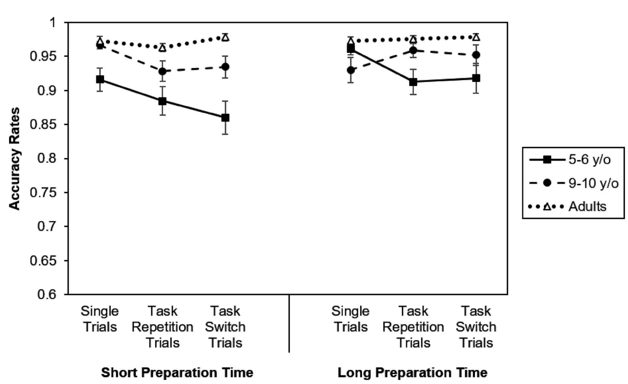

Figure 2. Accuracy rates by trial type (single, task repetition, task switch) for 5–6- year-olds, 9–10-year-olds, and adults as a function of preparation time. Error bars represent standard errors.

than the long preparation time (M_{short} = 88.86% vs. M_{long} = 93.04%), p = .008, no such difference was observed in 9–10-year-olds and adults (9–10-year-olds: M_{short} = 94.32% vs. M_{long} = 94.87%; adults: M_{short} = 97.15% vs. M_{long} = 97.59%), respectively, p = .574 and p = .209. Moreover, for the 5–6-year-olds, only the difference between single trials and task repetition trials in the long preparation time condition (M_{single} = 96.09%, vs. $M_{task\ repetition}$ = 91.25%) was significant, p = .012, revealing significant mixing costs. Conversely, 9–10-year-olds showed significant mixing costs in the short preparation time condition (M_{single} = 96.67% vs. $M_{task\ repetition}$ = 92.82%), p = .014. For adults, accuracy rates across trial types and preparation time revealed no significant mixing or switch costs, all ps >.079.

RTs. On RTs, a 3 (age group: 5–6 years, 9–10 years, adults) × 3 (trial type: single, task repetition, task switch) × 2 (preparation time: short, long) mixed ANOVA was performed. There were main effects of age, $F(2, 88) = 158.10$, $p < .001$, η_p^2 = .78, trial type, $F(2, 176) = 372.44$, $p < .001$, η_p^2 = .81, but not of preparation time, p = .290, and these effects were qualified by two-way interactions between age and trial type, $F(4, 176) = 8.65$, $p < .001$, η_p^2 = .16, and trial type and preparation time, $F(2, 176) = 22.38$, $p < .001$, η_p^2 = .20, and a significant three-way interaction between these factors, $F(4, 176) = 3.00$, p = .031, η_p^2 = .06. Although each age group showed significant mixing and switch costs, all ps <.001, these costs were overall higher for 5–6-year-olds (M_{single} = 1,241.47 ms, $M_{task\ repetition}$ = 1,869.75 ms and $M_{task\ switch}$ = 2,613.95 ms) than for 9–10-year-olds (M_{single} = 710.00 ms, $M_{task\ repetition}$ = 1,018.60 ms and $M_{task\ switch}$ = 1,219.11 ms) and adults (M_{single} = 485.20 ms, $M_{task\ repetition}$ = 662.61 ms and $M_{task\ switch}$ = 761.59 ms). Moreover, preparation time did not affect mixing costs in children (5–6-year-olds: M_{short} = 590.24 ms vs. M_{long} = 666.32 ms; 9–10-year-olds: M_{short} = 303.99 ms vs. M_{long} = 313.21 ms), all ps >.580, but it did in adults (M_{short} = 195.15 ms vs. M_{long} = 159.67 ms), p = .041. Conversely, switch costs were higher with short than long preparation times in each age group, and this difference was largest for 5–6-year-olds (5–6-year-olds: M_{short} = 1,034.47 ms vs. M_{long} = 453.93 ms; 9–10 year-olds: M_{short} = 281.91 ms vs. M_{long} = 119.10 ms; adults: M_{short} = 128.03 ms vs. M_{long} = 69.92 ms), all ps <.005 (Figure 3).

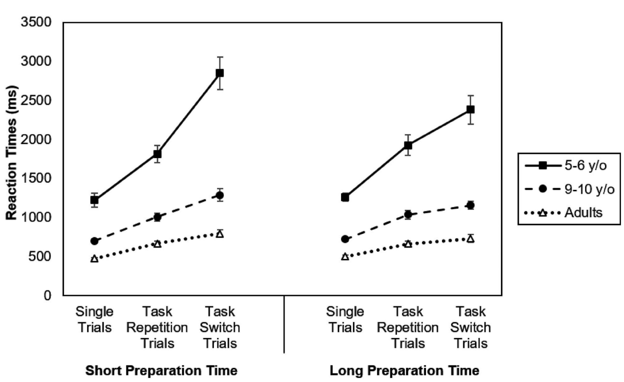

Figure 3. Reaction times (in milliseconds) for 5–6-year-olds, 9–10-year-olds, and adults as a function of preparation time. Error bars represent standard errors.

Task Selection

Task transition—*P* (switch). Task transition was examined with a 3 (age group: 5–6 years, 9–10 years, adults) × 2 (preparation time: short, long) mixed ANOVA performed on p(switch). The analysis revealed a main effect of preparation time, $F(1, 88)$ = 7.90, p = .006, η_p^2 = .08, but no effect of age, p = .353, and no significant interaction between preparation time and age, p = .275. Overall, pairwise comparisons indicated that participants switched tasks less often when preparation time was short than long, respectively, $M_{p(switch)}$ = 44.78% and $M_{p(switch)}$ = 48.62%, p = .005 (Figure 4). However, when comparing p(switch) between both conditions for each group, we found that there were significant differences between the short and long preparation time conditions in older children ($M_{p(switch)}$ = 46.24% and $M_{p(switch)}$ = 51.53%) and adults ($M_{p(switch)}$ = 43.63% and $M_{p(switch)}$ = 48.97%), respectively, p = .015 and p = .004, but no difference in younger children ($M_{p(switch)}$ = 44.47% and $M_{p(switch)}$ = 45.14%), p = .831.

Task selection equality—Relative difference between the frequency of each task. Task selection equality was analyzed with a 3 (age group: 5–6 years, 9–10 years, adults) × 2 (preparation time: short, long) mixed ANOVA performed on the relative difference between the two tasks. The ANOVA showed a main effect of age, $F(2, 88) = 8.19$, p = .001, η_p^2 = .16 but no effect of preparation time, p = .720, and no interaction, p = .871. Pairwise comparisons indicated that 5–6-year-olds did not perform the two tasks as equally often ($M_{difference}$ = 10.30%) as 9–10-year-olds ($M_{difference}$ = 5.00%) and adults ($M_{difference}$ = 5.28%), regardless of the preparation time duration (Figure 5), all ps >.003.

Task randomness—Strategy detection and type of strategy used. We examined task randomness with a 3 (age group: 5–6 years, 9–10 years, adults) × 2 (preparation time: short, long) mixed ANOVA to test to what extent participants used predictable strategies, and whether or not it varied according to age and/or preparation time. There were main effects of age, $F(2, 88)$ = 38.82, p = <.001 η_p^2 = .47, and preparation time, $F(1, 88) = 6.15$, p = .015, η_p^2 = .06, while the interaction did not reach significance, p = .113. Overall, pairwise comparisons indicated that 5–6-year-olds used significantly more nonrandom patterns or strategies (M = 2.59) than 9–10-year-olds (M = 0.73) and adults (M = 0.55), all ps <.001, and in all age groups, the use of strategies was overall slightly higher in the short preparation time condition than in the long preparation time condition (respectively, M = 1.46 and M = 1.05), p = .019 (Figure 6), although further analyses revealed that the difference between the two preparation time conditions was not significant for all age groups, all ps >.054.

Then, the type of strategies the participants used across age groups and preparation time durations was investigated with a multivariate analysis of variance (MANOVA). It revealed a significant difference in strategy type used based on age, $F(10, 344) = 9.45$, $p < .001$, Wilk's Λ = .62, η_p^2 = .21, but not based on preparation time, $F(5, 172) = 1.29$, p = .269, Wilk's Λ = .97, η_p^2 = .04, with no interaction between these two factors, p = .340. As there was no effect of preparation time, we ran another MANOVA without this factor and as illustrated in Figure 7; age had a main effect on the strategy repetition only, $F(1, 88) = 17.46$, $p < .001$, η_p^2 = .28, switch only, $F(1, 88) = 11.89$, $p < .001$, η_p^2 = .21, and one repetition and switch, $F(2, 88) = 3.88$, p = .024, η_p^2 = .08, but not on the two other strategies, all ps >.433. Pairwise

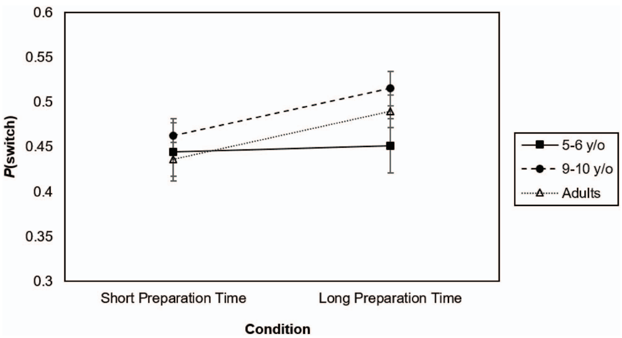

Figure 4. *P*(switch) for 5–6-year-olds, 9–10-year-olds, and adults as a function of preparation time. Error bars represent standard errors.

comparisons indicated that 5–6-year-olds used repetition only and switch only strategies more often than 9–10-year-olds and adults (repetition only: $M = 2.31$, $M = .06$, and $M = .29$, respectively, all *p*s $<.001$; switch only: $M = 1.52$, $M = .35$, and $M = .13$, respectively, *p*s $<.001$). 5–6-year-olds also significantly used the one repetition and switch strategy more than adults ($M = .90$ and $M = .26$, respectively), $p = .023$, but not than 9–10-year-olds, ($M = .45$), $p = .182$. All other comparisons were not significant, all *p*s $> .608$. In 5–6-year-olds, the repetition only strategy was not significantly used more frequently than the switch only strategy, $p = .232$, but more frequently than one repetition and switch, $p = .039$. No difference was observed between switch only and one repetition and switch, $p = .164$.

Discussion

The current study addressed the development of self-directed control by examining how 5- to 6-year-olds, 9- to 10-year-olds, and adults voluntarily switched between tasks. In particular, we explored the role of proactive and reactive control by using a short and a long preparation time. Contrary to our expectations, younger children showed a similar repetition bias to older children and adults, with a *p*(switch) value inferior to .5. However, following our predictions, their *p*(switch) was less sensitive to preparation time variations than for older children and adults, suggesting they engaged control more reactively than older groups. Moreover,

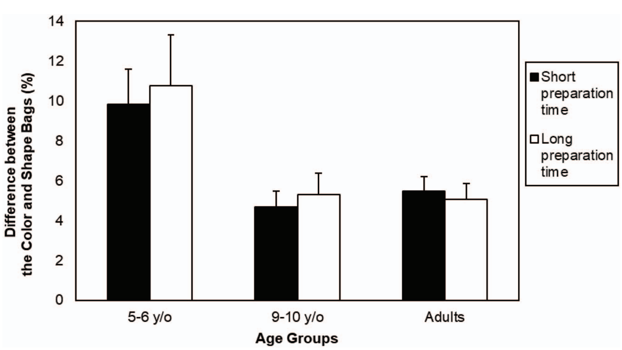

Figure 5. Difference between the two bags for 5–6-year-olds, 9–10-year-olds, and adults as a function of preparation time. Error bars represent standard errors.

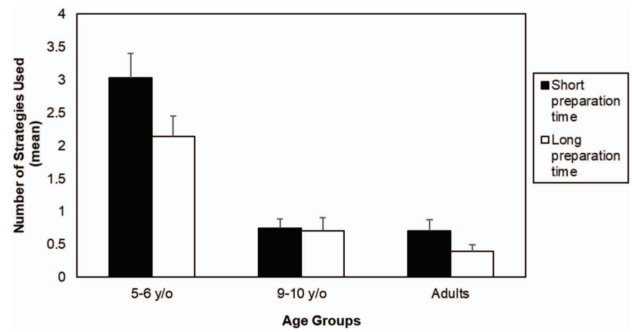

Figure 6. Strategy detection (mean) for 5–6-year-olds, 9–10-year-olds, and adults as a function of preparation time. Error bars represent standard errors.

younger children were significantly worse at performing the two tasks equally often, and used significantly more basic nonrandom strategies such as repeating systematically the task that had just been done, switching systematically between the two tasks or always switching after one repetition, reducing the cognitive demands of task selection.

Mixing and switch costs found in our experiment replicated the trend found in externally driven task switching paradigms in children (e.g., Chevalier & Blaye, 2009; Chevalier, Dauvier, & Blaye, 2018; Dauvier et al., 2012), suggesting that our child-friendly version of VTS appropriately tapped task switching. Furthermore, using this child-friendly VTS paradigm for the first time, we replicated previous findings from VTS studies in adults showing that participants had overall a *p*(switch) lower than .5 which even decreased with shorter preparation time for older children and adults (e.g., Arrington & Logan, 2005; Butler et al., 2011; Butler & Weywadt, 2013; Liefooghe et al., 2009; Yeung, 2010). This further suggests that our VTS paradigm captured self-directed control processes similar to those measured by classic VTS paradigms in adults, hence speaking to the success of our VTS adaptation.

Surprisingly, children showed a similar *p*(switch) to adults, against the expectation that the repetition bias would follow a U-shaped pattern with age, as hinted by prior studies showing a lower *p*(switch) during adolescence and aging than adulthood (Butler & Weywadt, 2013; Poljac et al., 2018; Terry & Sliwinski, 2012). In our study, the similar *p*(switch) across all age groups seemingly suggests no major differences between children and adults in the task selection processes involved in VTS. However, although the interaction between age and preparation time was not significant, younger children showed the same *p*(switch) with both preparation times, whereas *p*(switch) significantly increased with preparation time in older children and adults. Younger children may have used reactive control (i.e., availability heuristic) in VTS regardless of the amount of preparation time available, while older participants may have engaged proactive control (i.e., representativeness heuristic) when enough time was available. This would corroborate similar trends observed in task switching paradigms, but also in other paradigms both tapping externally driven cognitive control (e.g., Blackwell & Munakata, 2014; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier et al., 2015; Lucenet & Blaye, 2014). Nevertheless, further research is needed to clarify

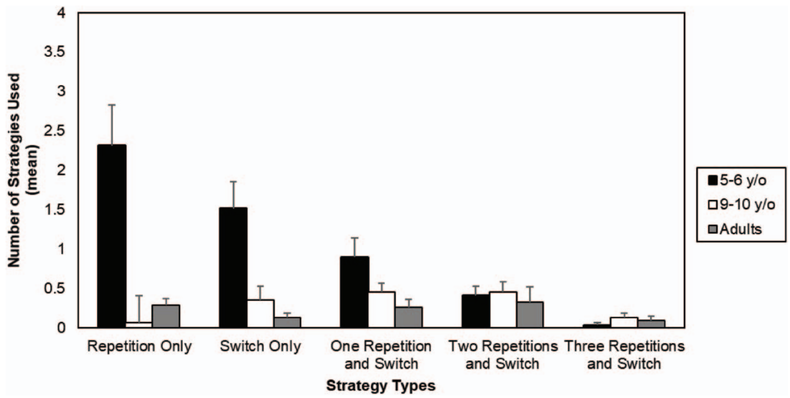

Figure 7. Use rate (mean) of each strategy from the more basic to the more complicated (left to right) as a function of age groups (5–6-year-olds, 9–10-year-olds, and adults). Error bars represent standard errors.

the role of reactive and proactive control in children's VTS performance. One promising option would be to couple our child-friendly VTS with physiological measurements such as event-related potentials, functional MRI, and pupil dilation, as these measures have shown sensitivity to reactive and proactive control engagement on other tasks (e.g., Chatham et al., 2012; Chevalier et al., 2015; Church et al., 2017).

As mentioned earlier, a drawback of using *p*(switch) as a unique measure of task selection (Arrington et al., 2014) is that it does not capture all aspects of VTS performance. In our study, the similar *p*(switch) found across age groups would suggest that children, and younger children in particular, have little difficulty with self-directed control, which would seem at odds with previous research on self-directed control development using different tasks (Barker et al., 2014; Snyder & Munakata, 2010, 2013; White, Burgess, & Hill, 2009). However, when considering measures other than *p*(switch), a different picture emerged, showing that task selection was particularly costly for younger children. In particular, younger children performed the two tasks less equally often than older children and adults.

Besides task selection difficulty, developmental limitations in numerical understanding may contribute to age-related differences in VTS performance. Indeed, learning number magnitudes develops slowly across childhood and although children as young as 5 years old can compare and add numerical quantities, they do not have adultlike exact number magnitude representations and they do not have much experience with numbers exceeding the 0–10 range (Barth, La Mont, Lipton, & Spelke, 2005, but see Siegler, 2016). Therefore, younger children may therefore have failed to add on from the last number and maintained this representation in working memory, leading them to struggle with performing the two tasks equally often. That said, counting strategies may not necessarily consist in counting how many times each task was played throughout the game, but instead counting trials within a run of trials before switching to the other task and starting from 1 again, which would require simpler numerical processing. Helping children more easily keep track of how many toys have been put into each bag by letting children see how many toys have been sorted within each bag should reduce age-related differences in future research, if these differences arise from limited numerical processing in younger children.

Another important finding was that, systematic, nonrandom strategies were more frequent in younger children than older children and adults. To account for this difference, one may argue that younger children simply did not understand the instruction of filling the two bags in a random fashion, even though this instruction was conveyed in a child-friendly manner through a bad elf that could otherwise guess how the target would be sorted and steal it. However, during practice, the use of systematic strategies was actively monitored and participants would progress onto the test trials of the mixed blocks only if they successfully played randomly, hence ensuring their understanding of this instruction. Indeed, as younger children required more practice than older children and adults (respectively, $M_{\text{number of practice}} = 1.43$, $M_{\text{number of practice}} = 1.21$ and $M_{\text{number of practice}} = 1.11$, all *p*s $<.019$) to master the instructions, one may argue that they may still have struggled to understand this instruction. However, when comparing younger children who needed only one practice round without the help of the experimenter—and therefore showed perfect understanding of the "randomness" instruction—to younger children who needed more than one practice round with the help of the experimenter, we observed no significant differences regarding how often they resorted to strategies (respectively, $M_{\text{number of strategy}} = 2.50$ and $M_{\text{number of strategy}} = 2.64$, $p = .804$). These findings further suggest that younger children understood the need to sort targets randomly but nevertheless relied on nonrandom strategies.

Young children may have been especially prone to resorting to strategies because of a lack of working memory abilities coupled with a difficulty to keep in mind the instructions of performing the two tasks equally often and in a random manner. Indeed, preschoolers, who have low working memory abilities, are more prone to goal neglect (i.e., failure to maintain a goal although how to achieve it is fully understood; see Marcovitch, Boseovski, & Knapp, 2007). Moreover, decrements in task performance when keeping prospective rule instructions in mind have been observed with both adults (e.g., Smith, 2003) and children (e.g., Leigh & Marcovitch, 2014; Nigro, Brandimonte, Cicogna, & Cosenza, 2014; Smith, Bayen, & Martin, 2010). In our study, younger children may have needed the appearance of the thief elf as a prospective cue to follow the instruction of being nonpredictable. It is therefore possible that processes underlying prospective memory abilities also affect task selection processes along with task performance processes. Consistently, commonality in processes between cognitive control and prospective memory has been emphasized in childhood (Brandimonte, Filippello, Coluccia, Altgassen, & Kliegel, 2011; Mahy, Moses, & Kliegel, 2014; Mahy & Munakata, 2015; Spiess, Meier, & Roebers, 2016).

Whether intentional or not, use of nonrandom strategies reduced the high cost of task selection demands specific to VTS for younger children. Having to hold complex rule instructions while performing VTS is particularly costly for younger children, and one way to reduce this cost is to favor the easiest rule instruction (i.e., putting about the same number of toys into each bag) over the most difficult rule instruction (i.e., performing the two tasks randomly). In prior research, removing the instruction of performing the two tasks in a random manner resulted in larger individual differences regarding task selection in adults, as indicated by large standard deviations in *p*(switch), suggesting that some participants were more likely to repeat tasks, whereas others were more likely to switch tasks (Arrington et al., 2014). Of particular interest, one of the two most frequent strategies among the younger children consisted in repeating the same task for long runs of trials, which led to a small *p*(switch) and would fit with the U-shaped changes in VTS performance with age, with adolescents and elderly people showing a greater repetition bias than adults (Butler & Weywadt, 2013; Poljac et al., 2018; Terry & Sliwinski, 2012). However, younger children also often used another strategy that consisted in switching systematically on every trial, which led to a very large *p*(switch) and could explain why the overall *p*(switch) at the group level was unexpectedly similar to that of older children and adults. Favoring the rule instruction of performing the two tasks equally often over the rule instruction of performing the two tasks randomly effectively reduces the cost of task selection. The selection of the repeat only and switch only as nonrandom strategies by younger children echoes the study of Arrington et al. (2014), as well as a recent study showing individual preferences in the use of strategies in a modified version of VTS in adults (Reissland & Manzey, 2016), and confirms that in task switching situations, children show higher variability in individual profiles when it comes to strategy selection (Dauvier et al., 2012; Moriguchi & Hiraki, 2011).

It is surprising that children systematically switched between tasks on every trial, given that this strategy must have resulted in heavier task switching demands. This finding further suggests that switching per se is not children's main difficulty when it comes to engaging efficient cognitive control. Switch costs were indeed not significant in terms of accuracy, even in younger children, although switching tasks is still more time consuming than repetitions, as attested by significant switch costs in terms of RTs. Unlike switching per se, selecting the appropriate task appeared particularly demanding as attested by (a) significant mixing costs for both accuracy and RTs, and (b) the use of nonrandom strategies by young children to reduce its costs. This corroborated studies using externally driven situations showing that task selection might be young children's main difficulty when engaging cognitive control (Chevalier, 2015; Chevalier et al., 2018; Deák, Ray, & Pick, 2004; Holt & Deák, 2015).

In our experiment, participants showed similar mixing and switch costs on RTs to those observed in externally driven situations. Similar processes may indeed be involved in both externally driven and self-directed control, which may mostly differ in task selection difficulty. Indeed, in VTS, while older children and adults adaptively selected tasks, younger children struggled in their task selection as attested by the fact that they performed the two tasks less equally often and used more nonrandom strategies. This confirms the recent idea that task selection is key in cognitive control (Broeker et al., 2018) and a major force driving cognitive development (Chevalier, 2015). Further, it also suggests that task selection is crucial when drawing the contrast between externally driven and self-directed control. For instance, consider the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948) compared with VTS. Both tap self-directed control as in VTS, participants have to decide on their own when to switch and what task to switch to, while in WCST, participants have to infer that the rule has changed and figure out on their own which rule is now relevant. However, WCST also taps externally driven control because the need to switch is externally supported by a short feedback from the experimenter after each choice. This feedback indicates when to switch but not toward what to switch to. These differences shed light on a continuum between externally driven and self-directed control based on the amount of task selection demands rather than a difference in nature, such as between reactive and proactive control.

To conclude, when voluntarily switching between tasks in VTS, 5- to 6-year-old children especially struggled to select between the two tasks, in comparison with 9- to 10-year-old children and adults, and used strategies which reduced task selection demands, even if these strategies involved frequent switching. These findings are strikingly similar to what has been previously found in tasks tapping externally driven control in children, speaking to the idea that these two forms of control form a continuum in which task selection demands vary rather than two discrete categories. As a consequence, better understanding task selection processes and their development open up new directions to design efficient interventions for assessing and supporting cognitive control in childhood.

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Chapter 4: Investigating the cognitive processes underlying goal identification in self-directed control development

Background

In this last empirical chapter, I used the child-friendly version of the voluntary task-switching paradigm presented in Chapter 3 to disentangle the two sub-processes of goal identification in self-directed control, namely context-tracking and task selection in children aged 5-6 years-old, 9-10 years-old and adults. To do so, in a first experiment, I manipulated the amount of environmental support provided which targeted context-tracking. In a second experiment, I manipulated the difficulties of the two tasks (symmetrical or asymmetrical) to specifically target task selection. I investigated how these manipulations influenced the three indices of VTS: p(switch), task balance and task randomness.

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Understanding autonomous behaviour development: Testing the respective contributions of context-tracking and task selection

Abstract

Gaining autonomy is a key aspect of growing up and support cognitive control development. However, little is known about how children engage cognitive control in an autonomous (or self-directed) fashion. Here, we propose that in order to successfully engage self-directed control, children identify and achieve goals by tracking contextual information and using this information to select relevant tasks. To disentangle the respective contributions of these processes, we manipulated the difficulty of context-tracking by providing or not environmental support (Study 1) and of task selection by varying task difficulty (a)symmetry (Study 2) in 5-6 and 9-10-year-olds, and adults. Results showed that, although both processes contribute to successful self-directed engagement of cognitive control, age-related progress mostly relates to context-tracking.

Key words: cognitive control development, self-directed control, context-tracking, task selection, voluntary task-switching

1. Introduction

Cognitive control, the goal-directed self-regulation of thoughts, actions and emotions, plays a critical role in children' daily lives. For instance, to answer a question asked by the teacher (i.e., the goal) at school, children have to adaptively engage cognitive control to inhibit their desires to directly give the answer but instead raise their hand first, to update information if another child has just given the same answer, and to switch to another answer if the one just given was wrong. Critically, with age, they are increasingly expected to do so without being explicitly prompted by the teacher. In other words, they need to become increasingly self-directed (as opposed to externally-driven) when engaging cognitive control. However, little is known about the cognitive processes underlying self-directed engagement of cognitive control. The current paper explores the role of two fundamental aspects of self-directed control which are context-tracking and task selection.

Self-directed control engagement is more challenging than externally-driven control engagement to children (Munakata, Snyder, & Chatham, 2012), probably because of the greater difficulty related to goal identification. Goals guide information processing and actions and are thus critical for cognitive control engagement (Miller & Cohen, 2001). Children struggle to identify goals from contextual cues, even when such cues are externally provided in the environment (e.g., a grey background to indicate sorting toys according to their colour), and largely contributing to immature cognitive control engagement in early childhood (Chevalier, 2015; Chevalier, Dauvier, & Blaye, 2018; Kray, Gaspard, Karbach, & Blaye, 2013). Indeed, when cue processing is facilitated or practiced, children show improved cognitive control performance (e.g., Chevalier & Blaye, 2009; Chevalier, Chatham, & Munakata, 2014). However, goals are particularly difficult to identify when no or few environmental cues are provided such as in situations involving self-directed control.

Successful goal identification involves two key cognitive processes that are likely to be especially challenging when cognitive control is engaged self-directedly. The first cognitive process is to keep track of the context (context-tracking). Contexts may involve changes in task demands or goals and may be influenced by past actions. In particular, attainment of a specific goal (e.g., prepare breakfast) may require a series of sub-goals (e.g., make coffee, cut bread, etc.). Therefore, one needs to keep track of contextual information including where one stands in a hierarchy of sub-goals and goals, or cues suggesting that a new goal should be pursued. The second cognitive process consists in using this contextual information to determine when and what behaviour should be engaged (task selection) in order to achieve sub-goals and goals. However, the relation between context-tracking and task selection may be bidirectional. Indeed, although context-tracking may guide task selection by providing information about sub-goals and goals, task selection may also influence the content of this information, requiring context-tracking to update it, based on task selection (i.e., once a task has been selected, this selection should be considered when one keeps track of the context). Working memory, which refers to the maintenance and manipulation of information in the cognitive system, is known to support both updating/maintenance of contextual information and manipulation of this information to select the relevant task. As such, working memory development (e.g., Camos & Barrouillet, 2018) is likely to drive progress in self-directed control engagement in childhood.

The respective contribution of context-tracking and task selection to self-directed control development may be examined with the voluntary task-switching paradigm (VTS; Arrington & Logan, 2004), in which individuals self-directedly select which task to perform following the instructions to perform each task equally often and in a random manner. Indeed, despite these instructions, adults often tend to repeat the same task more often than they switch between tasks, hence showing a lower probability of switching, noted *p*(switch) than what would be expected if they repeated and switched tasks equally often (i.e., *p*(switch) = .5; e.g., Arrington, Reiman, & Weaver, 2014; Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018). This *p*(switch) follows an inverted U-shaped pattern with adolescents and elderly people showing a lower *p*(switch) than adults (Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012).

However, in the only study examining VTS performance in children, 5-years-olds showed a similar *p*(switch) to 9-year-olds and young adults (Frick, Brandimonte, & Chevalier, 2019), perhaps suggesting that children show no specific difficulty in switching between tasks in the VTS. Yet, 5-year-old children selected one task more often than the other and relied on predictable strategies more than older children and adults did, hence failing to comply with instructions to select both tasks equally often and randomly. These results show that *p*(switch) does not capture all aspects of self-directed control in VTS, and are consistent with evidence of age-related progress during childhood in other tasks tapping self-directed control (Barker et al., 2014; Snyder & Munakata, 2010, 2013; White, Burgess, & Hill, 2009; for a review see Barker & Munakata, 2015). Interestingly, young children often switched between tasks on every trial (thus failing to select tasks randomly), suggesting that implementing a task switch *per se* is not the main difficulty for younger children. Implementing a predictable pattern may be a way for these children to reduce the high costs of context-tracking and task selection, hence pointing to these two processes as the main source of children's difficulty.

It is unclear whether children's difficulty with goal identification relates to keeping track of contextual information, selecting the task based on this information, or both. The present studies examined their respective contributions to self-directed control engagement and their relation. Specifically, Study 1 addressed whether decreasing the working memory demands on context-tracking by providing environmental support enhances VTS performance, while Study 2 varied the difficulty of task selection through task difficulty (a)symmetry. Finally, given the limitations of *p*(switch), we considered other indices that may more directly capture context-tracking and task selection, namely task balance and task randomness.

2. Study 1

Study 1 examined to what extent context-tracking contributes to age-related differences in self-directed control performance by providing environmental information about what has been done previously, therefore reducing the working memory demands related to this process. Specifically, in the environmental-support condition, they were shown how many times each task was played to help them keep track of which task they performed, whereas in the no-environmental-support condition, no such environmental information was provided, forcing participants to keep track of their performance on their own. Note that the environmental support did not directly signal which task to select, unlike task cues or alternating-runs rules as done in externally-driven or less externally-driven task-switching paradigms (e.g., Chevalier et al., 2018; Dauvier, Chevalier, & Blaye, 2012). To this end, 5-6 years-olds, 9-10 years-olds, and adults completed a child-friendly version of VTS (adapted from Frick et al., 2019). If 5-6-year-old children's difficulty is related to context-tracking, providing environmental support about previously performed tasks should improve their performance and reduce differences across age groups. Conversely, if the difficulty is rather related to the use of the information provided by context-tracking, therefore to task selection, the presence of environmental support should not affect performance. Specifically, we expected environmental support to affect task balance and randomness, because both indexes critically rely on contextual information. In contrast, it is less clear how providing environmental information would influence *p*(switch) as children can have a good *p*(switch) despite difficulties in tracking and using contextual information through the use of (maladaptive) systematic alternating strategies.

2.1. Methods

2.1.1. Participants

Participants included 30 five- to six-year-old children (*M* = 5.93 years, *SD* = .89, range: 5.00 – 6.85, 12 females), 30 nine- to ten-year-old children (*M* = 9.64 years, *SD* = .95, range: 9.03 – 10.99, 13 females), and 29 adults (*M* = 22.55 years, *SD* = 4.56, range: 18.21 – 33.02, 15 females). Ten additional participants were excluded: two failed the practice blocks, four wished to withdraw or performed only with the help of the experimenter, two fell outside of the age range and two due to an experimental error. All children were recruited from the local community and adults were undergraduate students enrolled in the local university. Parent consent was obtained for all children. Parents received £10 compensation, and children received an age-appropriate prize. Adults received course credits. This study received approval from the Ethics Committee of the University of Edinburgh.

Parent filled out a demographic questionnaire to asses socio-economic status (SES) in which they informed their postcode to determine their Scottish Index of Multiple Deprivation (SIMD) quintile index (Scottish Governement, 2020) ranging from 1 = lowest income to 5 = highest income. This information was missing for five children. Half of the children came from the area with the highest income (54.54%) while the other half came from areas with lower income, revealing that children SES varied between middle to high SES background (see Table 1). Participants were mostly Caucasian although this information was not collected due to the ethical reasons.

Table 1. Quintile Scottish Index of Multiple Deprivation (SIMD) for 5-6 year-olds and 9-10 year-olds as a function of their residence areas.

	Quintile SIMD Scores				
	1	2	3	4	5
5-6 year-olds	3.57%	17.86%	21.43%	3.57%	53.57%
9-10 year-olds	7.41%	7.41%	14.81%	14.81%	55.56%

2.1.2. Material and procedure

All participants were tested individually in the laboratory. They completed a child-friendly VTS similar to Frick et al. (2019) presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). Participants had to voluntarily switch between matching bidimensional targets (e.g., a blue teddy) according to their colour (i.e., sending it to the colour bag) or shape (i.e., sending it to the shape bag; Figure 1). Each trial started with a fixation cross. After 1,500 ms, the fixation cross was replaced with the onset of the target that remained on screen until participants' response on the response box. After the response, the target was replaced by a present that remained for 500 ms and then appeared into the chosen bag chosen for 500 ms. In the environmental support condition, the present remained visible into the bag during the task, whereas it disappeared from the bag at the onset of the next trial in the no environmental support condition. All participants were tested in the two conditions (order counterbalanced).

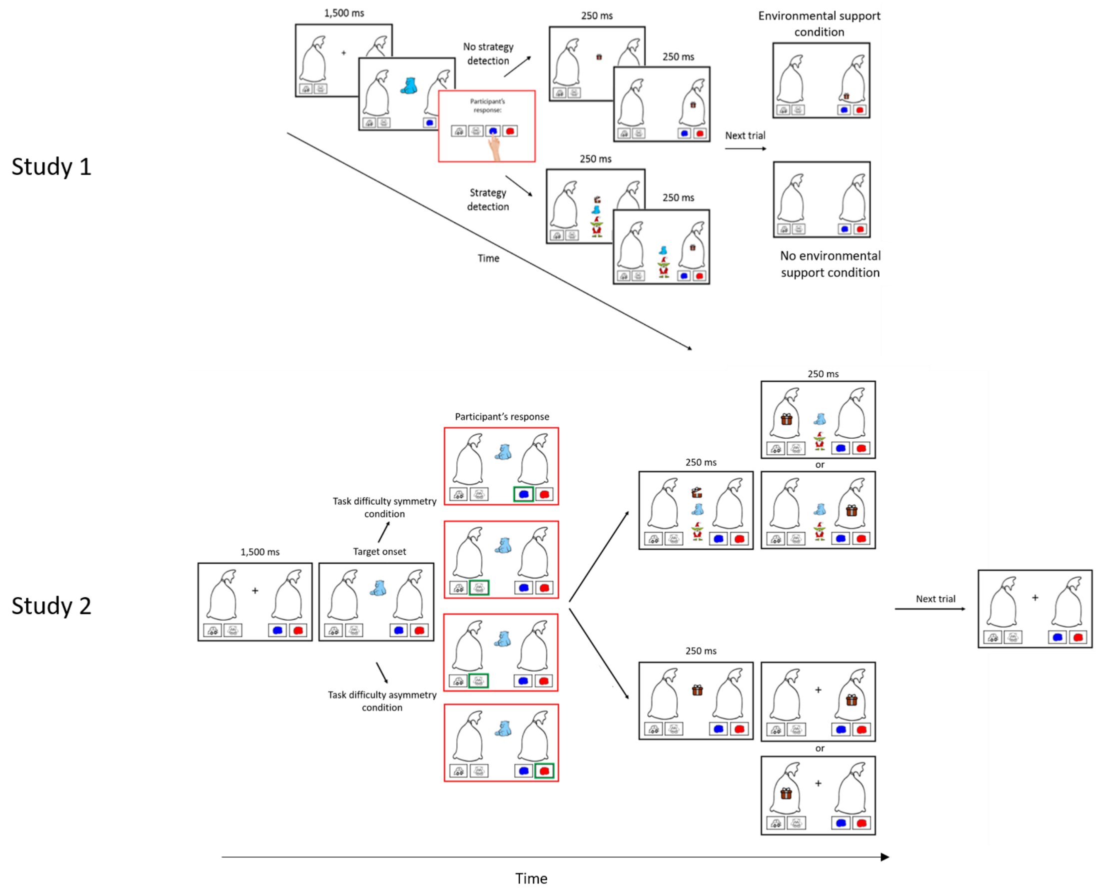

Figure 1. Child-friendly voluntary task switching paradigm. Children had to voluntarily match bidimensional stimuli according to their colour or shape with the general instructions to perform the colour and shapes games equally often (i.e., place about the same number of targets in the Colour or Shape bags) and in random manner (i.e., not using a predictable strategy to avoid the theft of the target by an elf). In Study 1 (top figure), the presents remained into the bag in the next trial (environmental support condition) or disappeared from the bag in the next trial (no environmental support condition). In Study 2 (bottom figure), children had to match targets with the same dimensions in both tasks (task difficulty symmetry condition) to match targets with the same dimensions in one task whereas they had to match targets with the opposite dimensions in the other task (task difficulty asymmetry condition).

Participants first completed two single-blocks (one colour, one shape; order counter-balanced across participants) in which they were instructed to sort the targets either only by colour or only by shape on all trials. Each block comprised four practice trials (repeated if more than two errors with a maximum of two times) followed by 16 test trials. Then, participants completed two mixed-blocks where they had to voluntarily switch between the two tasks, that is, fill the two bags with about the same number of toys. Importantly, they were instructed to make sure a thief elf could not predict how they would sort the toys. The following two demonstrations were provided. First, the experimenter demonstrated a strict alternation between the two bags on seven trials (e.g., colour-shape-colour-shape-colour-shape-colour), which resulted in the elf stealing the toy. Second, the experimenter demonstrated how to successfully put about the same number of toys into each bag while not following a predictable order to prevent the elf from stealing toys (e.g., colour-colour-shape-colour-shape-shape-shape-colour-colour-shape-colour-colour). Participants then completed 16 practice trials which were repeated (maximum three times) if (a) one bag contained more than 10 toys (62.5%), (b) the elf detected one of the ten predictable patterns (see Data Processing and Analyses section) and/or (c) more than eight errors (50%) were made. No guidance was provided for the first warm-up block performed but if repetition was then needed, guidance by the experimenter was provided. Only those participants who successfully passed the practice block were included in the sample. Participants then completed two series of 40 test trials each (80 test trials per condition, 160 in total).

2.1.3. Data processing

P(switch) was calculated by dividing the number of task switch trials (i.e., different task on trials *n* and *n*-1) by the total number of task switch and task repetition trials (i.e., same task on trials *n* and *n*-1).

Task balance consisted in the difference between the proportion of Colour and Shape trials. A score was computed depending on how far the difference from 0 was. For instance, a difference of 0.125 was scored 1, 0.5 was scored 4 and so forth.

Task randomness was measured via occurrences of ten different strategies ranging from five basic to complex sequences: ‘Repetition Only’ or ‘Switch Only’ detected over seven trials (e.g., colour-colour-colour-colour-colour-colour-colour or colour-shape-colour-shape-colour-shape-colour, respectively), ‘One Repetition and Switch’ detected over nine trials (e.g., colour-colour-shape-shape-colour-colour-shape-shape-colour), ‘Two Repetition and Switch’ detected over eleven trials (e.g., colour-colour-colour-shape-shape-shape-colour-colour-colour-shape-shape) and ‘Three Repetition and Switch’ detected over thirteen trials (e.g., colour-colour-colour-colour-shape-shape-shape-shape-colour-colour-colour-colour-shape). The frequency of these strategies was used during the game (i.e., when the elf showed up) to index task randomness. Moreover, our analyses also focused on the qualitative type of strategies.

2.1.4. Data analyses

P(switch), task balance and task randomness were analysed using a Linear Mixed Model (LMM 1), and two Generalized Linear Mixed Models (GLMM 1 and GLMM 2) with a Poisson distribution for count data, respectively. These models were fit in R version 4.0.2 (R Core Team, 2020) using the *lme4* package (Bates, Mächler, & Bolker, 2015). LMM 1 and GLMM 1 contained with age group (5-6 years-old, 9-10 years-old and adults) and environmental support condition (no environmental support, environmental support) as fixed effects and Participant as a random effect with all possible interactions. GLMM 2 included age group, environmental support condition and strategy type (Repetition Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetition and Switch) as fixed effects and Participant as a random effect with all interactions possible using the

BOBYQA optimization (Powell, 2009). On lmer/glmer output we performed mixed model ANOVA tables via Likelihood Ratio Test using the *mixed* function from the *afex* package (Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020). This function fits the full model and then versions thereof in which a single effect is removed comparing the reduced model to the full model. Pairwise comparisons were used with Tukey's adjustments when there were multiplicity issues using the emmeans package (Lenth, 2020) and estimated marginal means (EMMs) are reported. Plots of the results were obtained using the *ggeffects* and *ggplot2* packages (Hadley, 2016; Lüdecke, 2018) and error bars represent confidence intervals.

2.2. Results

Results regarding task performance indexed by accuracy and reaction times (RTs) are available in Supplemental Material (I).

2.2.1. P(switch)

There were no effects of age group and environmental support condition and no interaction, *ps* > .142, indicating similar *p*(switch) rates across age groups and environmental support conditions (Figure 2).

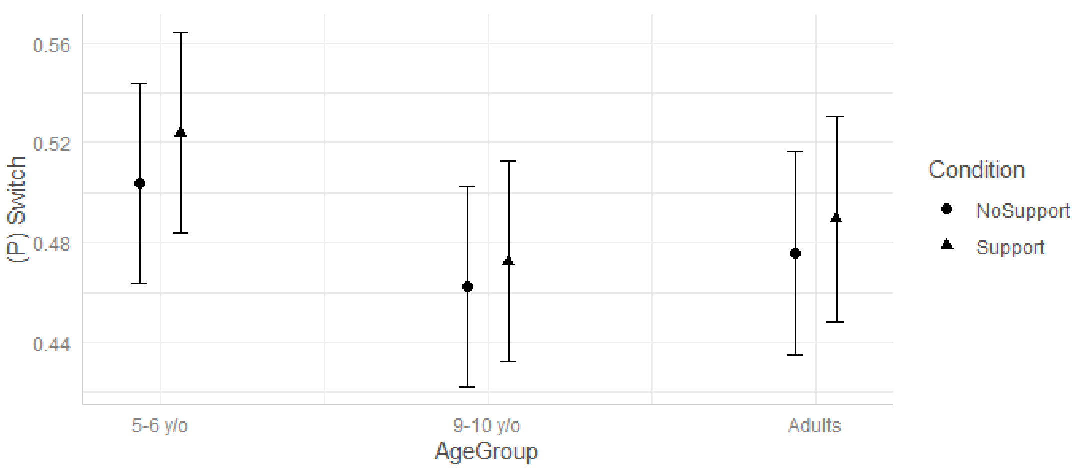

Figure 2. *P*(switch) as a function of age group (5-6 year-olds, 9-10 year-olds, adults) and environmental support condition (environmental support, no environmental support). All age

groups showed similar *p*(switch) which did not differ across environmental support conditions.

2.2.2. Task balance

There were main effects of age group, $\chi^2 = 9.44$, $df = 2$, $p = .009$, and environmental support condition, $\chi^2 = 58.71$, $df = 1$, $p < .001$, on whether participants performed the two task equally often. 5-6 year-olds and 9-10 year-olds performed the two task less equally often than adults ($M_{\text{5-6 year-olds}} = 1.56$ *vs.* $M_{\text{9-10 year-olds}} = 1.52$ *vs.* $M_{\text{adults}} = .83$; $ps < .021$), but they did not differ from each other, $p = .988$. Participants performed the two tasks more equally often with ($M = .77$) than without ($M = 2.06$) environmental support. Importantly, age group and environmental support condition interacted, $\chi^2 = 7.30$, $df = 2$, $p = .026$ (Figure 3), which revealed that the no environmental support condition, adults were better than younger and older children at performing the two tasks equally often ($M_{\text{5-6 year-olds}} = 3.26$ *vs.* $M_{\text{9-10 year-olds}} = 2.42$ *vs.* $M_{\text{adults}} = 1.10$; $ps < .005$) with no difference between children, $p = .310$, whereas no differences across age groups were observed with environmental support, $ps > .382$.

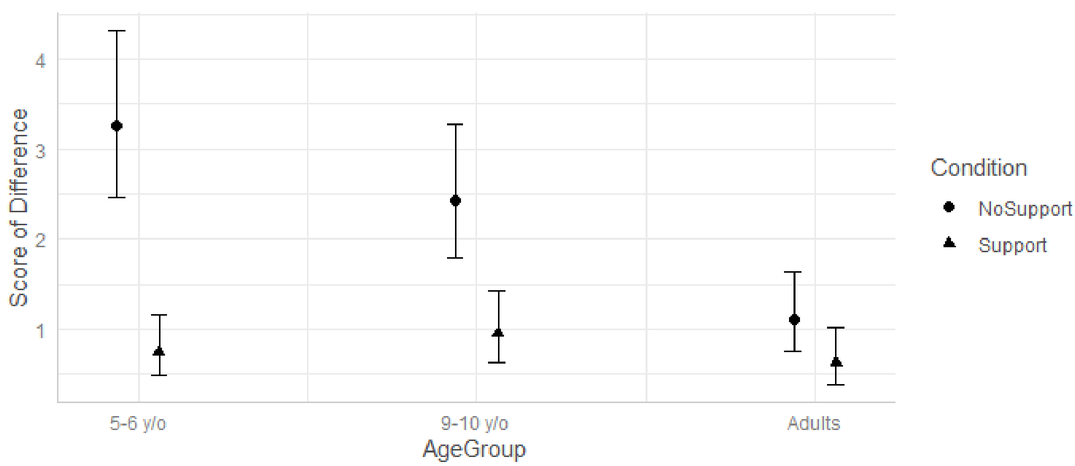

Figure 3. Score of difference as a function of age group (5-6 year-olds, 9-10 year-olds, adults) and environmental support condition (environmental support, no environmental support).

Error bars represent standard errors. Children showed greater asymmetry between the two tasks in the no environmental condition than in the environmental condition than adults. No differences were observed between age groups in the environmental support condition.

2.2.3. Task randomness

The full model comprising main effects and all possible interactions did not converge with the BOBYQA optimization, we therefore reduced this model removing the highest order three-way AgeGroup X EnvironmentalSupportCondition X StrategyType interaction, and this reduced model converged, producing stable results.

On strategy occurrences, there were effects of age group, $\chi^2 = 21.19$, $df = 2$, $p < .001$, and strategy type, $\chi^2 = 75.20$, $df = 4$, $p < .001$, but not of environmental support condition, $p = .436$ (Figure 4). Overall, 5-6 year-olds used more predictable strategies than 9-10 year-olds who used more strategies than adults ($M_{\text{5-6 year-olds}} = .32$ *vs.* $M_{\text{9-10 year-olds}} = .19$ *vs.* $M_{\text{adults}} = .10$; $ps < .048$). Participants used significantly more the ‘One Repetition and Switch’ strategy more than other strategies ($M_{\text{Repetition Only}} = .20$ *vs.* $M_{\text{Switch Only}} = .36$ *vs.* $M_{\text{One Repetition and Switch}} = .42$ *vs.* $M_{\text{Two Repetitions and Switch}} = .17$ *vs.* $M_{\text{Three Repetitions and Switch}} = 04$, $ps < .015$), but this strategy did not differ from the use of the ‘Switch Only’ strategy, $p = .930$. Age group interacted with strategy type, $\chi^2 = 40.73$, $df = 8$, $p < .001$. 5-6 year-olds used more the ‘Switch Only’ strategy than other strategies ($M_{\text{Repetition Only}} = .59$ *vs.* $M_{\text{Switch Only}} = 1.22$ *vs.* $M_{\text{One Repetition and Switch}} = .62$ *vs.* $M_{\text{Two Repetitions and Switch}} = .11$ *vs.* $M_{\text{Three Repetitions and Switch}} = .06$; $ps < .001$). 9-10 year-olds used more the ‘Switch Only’ and ‘One Repetition and Switch’ strategies than the ‘Three Repetitions and Switch’ strategy ($M_{\text{Switch Only}} = .33$ *vs.* $M_{\text{One Repetition and Switch}} = .35$ *vs.* $M_{\text{Three Repetitions and Switch}} = .05$; $ps < .018$). No other differences were observed, $ps > .079$. Adults used more the ‘One Repetition and Switch’ strategy than the ‘Repetition Only’ and ‘Three Repetitions and Switch’ strategies ($M_{\text{Repetition Only}} = .07$ *vs.* $M_{\text{One Repetition and Switch}} = .34$ *vs.* M_{Three}

$_{\text{Repetitions and Switch}} = .02$; *ps* < .029). Finally, 5-6 year-olds used more the ‘Repetition Only’ and ‘Switch Only’ strategies than 9-10 year-olds and adults (9-10 year-olds: $M_{\text{Repetition Only}} = .20$; adults: $M_{\text{Switch Only}} = .12$; *ps* < .004) with no differences between these two latter age groups, ps > .055. Other comparisons were not significant, *ps* > .075.

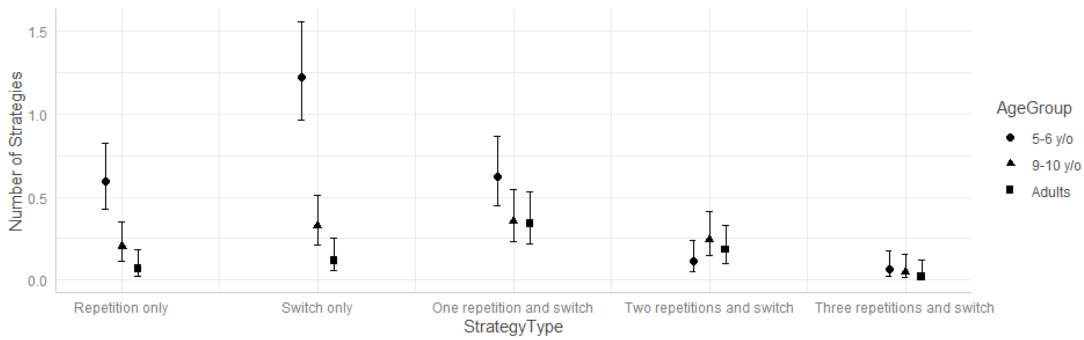

Figure 4. Number of strategy used as a function of the type of strategies (Repeat Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetitions and Switch) and age group (5-6 year-olds, 9-10 year-olds, adults). 5-6 year-olds used significantly more strategies (‘Repetition Only’, ‘Switch Only’) than other age groups and used preferentially the ‘Switch Only’ strategy.

2.3.Discussion

In line with our prediction, providing environmental support about previously performed tasks enhanced task balance in children, but not in adults. This suggests that part of children’s difficulty in engaging cognitive control self-directedly stems from sub-optimal context-tracking. Note that both younger and older children showed poorer task balance performance than adults, revealing that difficulties in self-directed situations remain until at least late childhood. However, contrary to our expectation, task randomness was not affected by environmental support. With or without environmental support, younger children relied more on the ‘Switch Only’ strategy than older children and adults. As such, task randomness seems less sensitive to context-tracking than task balance, and may instead mostly reflect task selection.

3. Study 2

Study 2 addressed the role of task selection in children’s VTS performance by manipulating task difficulty (a)symmetry. Indeed, task asymmetry has been shown to significantly bias participants to repeat the harder task more than the easier task, as the former task is the most implemented in working memory (Liefooghe, Demanet, & Vandierendonck, 2010; Millington, Poljac, & Yeung, 2013; Poljac et al., 2018; Weaver & Arrington, 2010; Yeung, 2010). In particular, the difficult task engages working memory to a larger extent than the easy task, making it more difficult to move away from this task, as there are less resources left for switching. If so, one would expect lower *p*(switch) as well as lower task balance and task randomness with asymmetrical than symmetrical task difficulty. Importantly, based on Study 1 findings, if task randomness reflects task selection to a greater extent than task balance, then task randomness should be the index most affected by task difficulty asymmetry. To this end, 5-6 years-old and 9-10 years-old children as well as adults completed a child-adapted version of VTS similar to Study 1. In the task difficulty symmetry condition, participants performed the same two tasks (‘regular’ colour and shape matching) as in Study 1. In the task difficulty asymmetry condition, participants performed the regular shape matching task (easy) and a ‘reversed’ colour-matching task in which they had to match the target to the response option of the other colour (difficult). We expected lower accuracy and longer RTs with asymmetric than symmetric task difficulty. More critically, we expected that if task selection is an important source of difficulty, then task difficulty asymmetry should affect *p*(switch), task balance, and—perhaps to an even greater extent—task randomness. Further, these effects should be more pronounced in younger than older participants. In contrast, if task selection is relatively trivial in VTS, then task difficulty asymmetry should affect response times and accuracy, but not the other indices.

3.1. Methods

3.1.1. Participants

Participants were 30 5-6 year-old children (M_{age} = 5.95 years, SD_{age} = 0.55 years, range = 5.00-6.90 years, 17 females), 30 9-10 year-old children (M_{age} = 9.98, SD_{age} = 0.53, range = 6.08-10.84, 15 females) and 30 adults (M_{age} = 20.68, SD_{age} = 1.81, range = 18.07-26.15, 15 females). All children were recruited at the same private school and adults were students enrolled at the university of the same city. A parental consent was obtained for each child who also gives a verbal and written assent to participate. Children received age-appropriate prices and adults received 2€ for their participation. This study received approval from the Ethics Committee of the University of Edinburgh as well as from the participating school. Participants were mostly Caucasian and children, as they came from the same private school, had the same SES background although this information was not collected.

3.1.2. Material and procedure

Children were tested in a quiet room within the school and adults were tested in a quiet room at the university. They completed a child-friendly voluntary task-switching paradigm similar to Study 1 presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). The procedure and number of trials were the same than in Study 1. The exception was that this time, participants entered their responses by pressing one of the four buttons (i.e., ‘q’, ‘w’, ‘o’, ‘p’) on a QWERTY keyboard. All participants completed two conditions (Figure 1). In the task symmetry condition, which was similar to the no environmental support condition in Study 1, participants were told to match the targets either with the button of the same Colour or with the button of the same Shape, the task symmetry condition. Conversely, in the task asymmetry condition, they had to match the target with the button of the same dimension for one game (e.g., match the targets with the button of the same shape when playing the Shape game) and to match the target with the button of the different dimension for the other game (e.g., match the targets with the button of the different colour when playing the Colour game). The order of the two working memory demands conditions was counter-balanced across participants.

3.1.3. Data processing

Task performance on the easy and hard tasks on single-task blocks within the higher working memory demands was examined through accuracy and response time (RTs) to ensure that these two tasks had different difficulty. These analyses were performed after discarding the first trial of each block. Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). Only RTs for correct trials preceded by correct trials were kept. Finally, RTs were trimmed out if they were under 200 ms, to account for accidental button presses, or greater than 3 standard deviations above the mean of each participant (computed separately for trials from single blocks, and task repetition and task switch trials from mixed blocks) or 10,000 ms.

P(switch), task balance and task randomness were computed using the same procedure than in Study 1.

3.1.4. Data analyses

Our analyses first focused on whether the supposedly easy task was less costly than the difficult task in terms of accuracy and averaged RTs within the task difficulty asymmetry condition. As such, a GLMM and LMM were performed with age group (5-6 year-olds, 9-10 year-olds and adults) and task difficulty (easy, difficult) as fixed effects and Participant as a random effect. Then, *p*(switch), task balance and task randomness were analysed in the similar manner than Study 1 with the difference that the task difficulty condition (symmetry, asymmetry) replaced the environmental support condition. Estimated marginal means and plots with confidence intervals as error bars are reported and presented.

3.2.Results

Results regarding task performance indexed by accuracy and reaction times (RTs) are available in Supplemental Material (II).

3.2.1. Easy task vs. hard task – Accuracy rates and RTs

The analysis performed on the accuracy measure showed a main effect of task difficulty, $\chi^2 = 34.72$, $df = 1$, $p < .001$, but not of age group, $p = .498$. Accuracy was lower in the harder task than in the easier task ($M_{\text{hard}} = .94$ vs. $M_{\text{easy}} = .98$; $p < .001$). Age group significantly interacted with task difficulty, $\chi^2 = 21.91$, $df = 2$, $p < .001$. 5-6-year-olds and adults were significantly less accurate when the task was difficult than when the task was easy (5-6 years-old: $M_{\text{easy}} = .99$ *vs.* $M_{\text{difficult}} = .91$; adults: $M_{\text{easy}} = .98$ *vs.* $M_{\text{hard}} = .95$; *ps* <.002), whereas no difference in terms of accuracy between the easy and the hard task was observed for 9-10-year-olds, $p = .906$. On RTs, there were main effects of age group, $\chi^2 = 97.48$, $df = 2$, $p < .001$, and task difficulty, $\chi^2 = 63.53$, $df = 1$, $p < .001$, but no interaction between these factors, $p = .219$. Overall, 5-6 year-olds were significantly slower than 9-10 year-olds, and 9-10 year-olds were significantly slower than adults ($M_{\text{5-6 year-olds}} = 7.28$ log-transformed ms (ln ms) *vs.* $M_{\text{9-10 year-olds}} = 6.74$ ln ms vs. $M_{\text{adults}} = 6.40$ ln ms; *ps* < .001). Moreover, participants were significantly slower on the difficult task than on the easy task ($M_{\text{easy}} = 6.64$ ln ms vs. $M_{\text{difficult}} = 6.98$ ln ms).

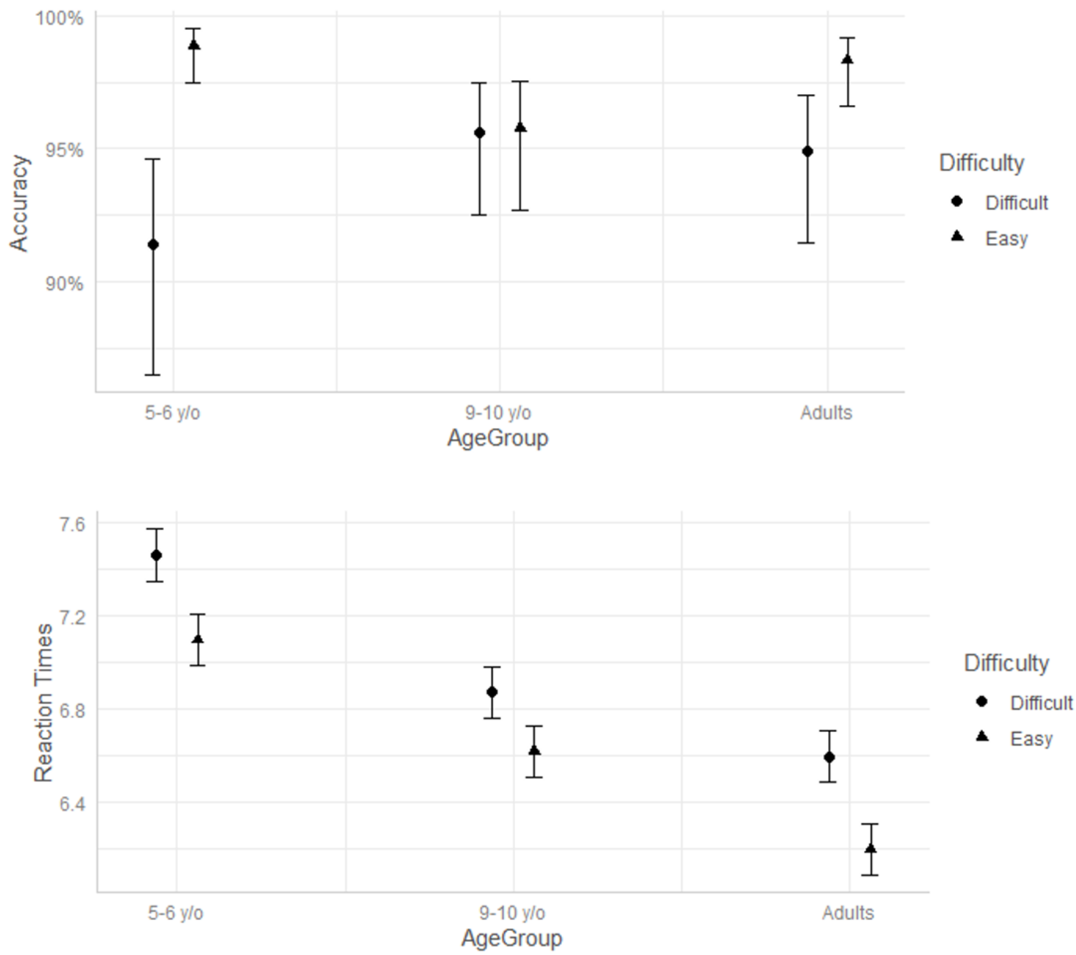

Figure 5. Accuracy and log RTs as a function of age group (5-6 year-olds, 9-10 year-olds and adults) and task difficulty (easy task, hard task). Accuracy was lower and log RTs were higher in the hard task than in the easy task.

3.2.2. P(switch)

On *p*(switch), there were a significant main effect of age group, $\chi^2 = 9.77$, $df = 2$, $p = .008$, but no effect of task difficulty (a)symmetry condition and no interaction, $ps > .155$. 9-10 year-olds switched significantly more than adults, but not than 5-6 year-olds ($M_{\text{5-6 year-olds}} = .49$ *vs.* $M_{\text{9-10 year-olds}} = .55$ *vs.* $M_{\text{adults}} = .47$; $p = .008$ and $p = .071$) and the two latter age groups did not differ, $p = .690$.

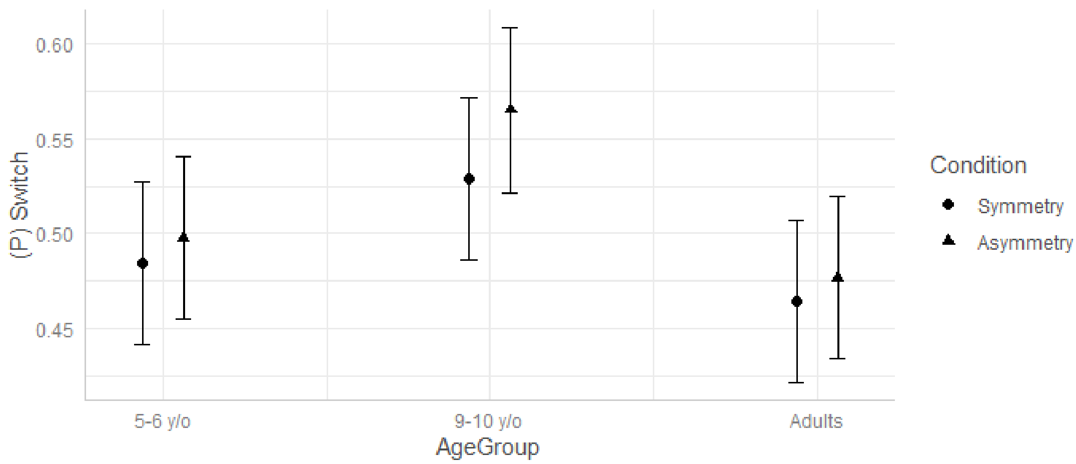

Figure 6. *P*(switch) as a function of age group (5-6 year-olds, 9-10 year-olds, adults) and task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry). 5-6 year-olds and adults showed similar *p*(switch) whereas 9-10 year-olds showed higher *p*(switch) than adults. *P*(switch) did not vary as a function of task difficulty (a)symmetry conditions.

3.2.3. *Task balance*

On task balance, one subject was removed because he/she has a score of 49 whereas the maximum score for other subjects was 23.

There was a significant main effect of age group, $\chi^2 = 7.29$, $df = 2$, $p = .026$, and task difficulty a(symmetry) condition, $\chi^2 = 7.48$, $df = 1$, $p = .006$, but no interaction between these factors, $p = .123$, on how participants performed the two tasks equally often. 5-6-year-olds showed a significantly greater asymmetry in performing the two tasks in comparison to adults, but did not differ from 9-10 year-olds ($M_{\text{5-6 year-olds}} = 3.39$ *vs.* $M_{\text{9-10 year-olds}} = 2.31$ *vs.* $M_{\text{adults}} = 2.19$; $p = .031$ and $p = .067$). 9-10 year-olds and adults did not differ from each other, $p = .950$. who did not differ from one another, $p = .954$. Surprisingly, participants performed significantly less equally often the two tasks in the task difficulty symmetry condition than in the task difficulty asymmetry condition ($M_{\text{task difficulty symmetry condition}}$ = 2.91 *vs.* $M_{\text{task difficulty asymmetry condition}}$ = 2.29).

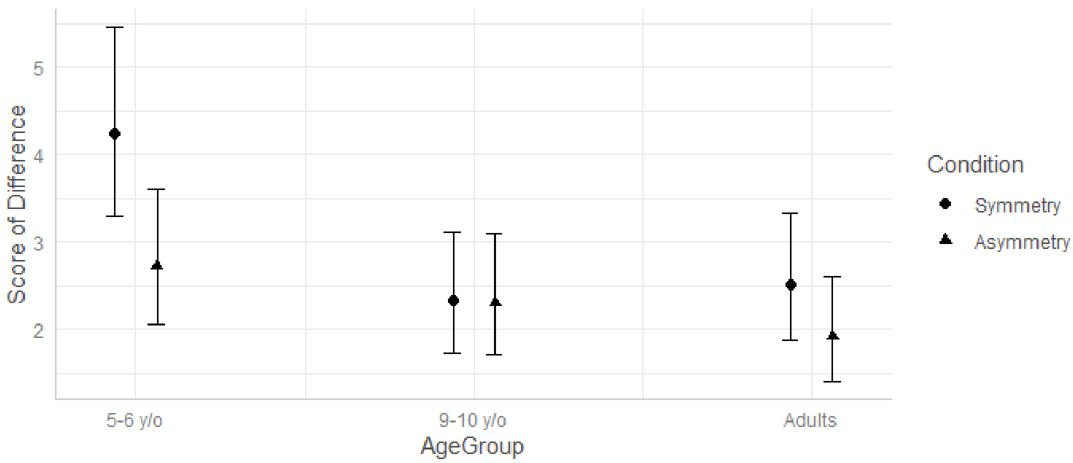

Figure 7. Score of difference as a function of age group (5-6 year-olds, 9-10 year-olds, adults) and task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry). 5-6 year-olds showed greater asymmetry between the two tasks selection than 9-10 year-olds and adults. The two latter did not differ. Participants showed greater asymmetry regarding task balance in the task difficulty symmetry condition than in the task difficulty asymmetry condition.

3.2.4. Task randomness

The full model comprising the main effects and all possible interactions did not converge with the BOBYQA optimization. As in Study 1, we first removed the higher three-way interaction and ran the model again, which again did not converge. Using plots, we identified that some values of combinations of factor levels had zero variance, we therefore subset the data by removing those with zero variance. This reduced model finally converged but produced warning which disappeared when removing the TaskDifficulty(A)symmetryCondition X StrategyType interaction. However, when keeping the AgeGroup X StrategyType interaction led to inestimable estimates. We therefore removed this interaction and report the reduced converging model containing the main effects and the AgeGroup X TaskDifficulty(A)symmetryCondition interaction.

This model revealed main effects of age group, $\chi^2 = 6.83$, $df = 2$, $p = .009$, task difficulty (a)symmetry condition, $\chi^2 = 4.48$, $df = 1$, $p = .034$, and strategy type, $\chi^2 = 68.35$, $df = 4$, $p < .001$, on strategy occurrences. 5-6 year-olds used significantly more strategies than 9-10 year-olds, who used significantly more strategies than adults ($M_{\text{5-6 year-olds}} = .41$ *vs.* $M_{\text{9-10 year-olds}} = .27$ *vs.* $M_{\text{adults}} = .14$; *ps* $< .031$). Participants used significantly more strategy in the task difficulty asymmetry condition than in the task symmetry condition ($M_{\text{task difficulty symmetry condition}} = .23$ *vs.* $M_{\text{task difficulty asymmetry condition}} = .30$), and used more the 'Switch Only' and 'One Repetition and Switch' strategies than other strategies ($M_{\text{Repetition Only}} = .31$ *vs.* $M_{\text{Switch Only}} = .69$ *vs.* $M_{\text{One Repetition and Switch}} = .56$ *vs.* $M_{\text{Two Repetitions and Switch}} = .17$ *vs.* $M_{\text{Three Repetitions and Switch}} = .06$; *ps* $< .001$), with no difference between these two strategies, $p = .438$.

The interaction between age group and strategy type was not significant, $p = .570$.

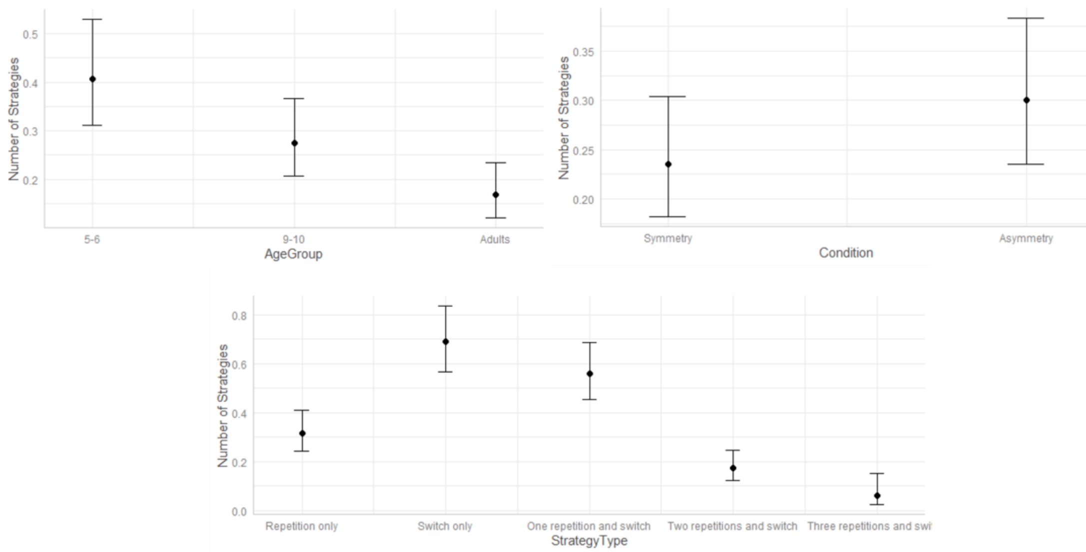

Figure 7. Number of strategy used as a function of age group (5-6 year-olds, 9-10 year-olds, adults; top left figure), task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry; top right figure) and strategy type (Repeat Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetitions and Switch; bottom figure). 5-6 year-olds used more strategies than 9-10 year-olds who used more strategies than adults. Participants used more strategies in the task difficulty asymmetry condition than in the task difficulty symmetry condition. Participants used more the ‘Switch Only’ and ‘One Repetition and Switch’ strategies than other strategies.

3.3.Discussion

As expected, lower accuracy and higher RTs were observed in the task difficulty asymmetry condition than in the task difficulty symmetry condition (see Supplemental Material, Study 2), which speaks to the success of our manipulation.

Task balance and task randomness were differently affected by the task difficulty (a)symmetry, whereas *p*(switch) was not. Specifically, when task difficulty was asymmetrical, participants used significantly more predictable strategies. Given that the model on task randomness did not allow to test for the interaction between age group and strategy type, and task difficulty (a)symmetry condition and strategy type, we conducted a mixed ANOVA to explore these possible interactions (see Supplemental Material, III). This analysis produced similar main effects than our GLMM but more specifically revealed that participants used more the ‘Switch Only’ strategy in the task difficulty asymmetry condition than in the task difficulty symmetry condition. This finding suggests that task selection does indeed contribute to participants’ difficulty in VTS, and given the lack of interaction between age group and task difficulty (a)symmetry, this contribution may be similar for children and adults. Indeed, as the ‘Switch Only’ strategy is generally more frequently used by younger children than the other age groups, increasing the difficulty of task selection may make older age groups revert to less mature engagement of cognitive control, more akin to younger children. An important question is why increasing this difficulty results in more frequent use of ‘Switch Only’ but not the other strategies. One plausible answer is that the use of the ‘Switch Only’ strategy reduces demands on task selection and context-tracking (i.e., one only needs to know what task has just been performed in order to select the new task, alleviating the working memory demands on context-tracking and task selection), whereas other strategies minimise task selection but at the cost of relatively high context-tracking demands (i.e., need to maintain information about previously performed tasks over several trials). Although one may go as far as to argue that task difficulty asymmetry may have mostly affected context-tracking, this seems implausible as we reported that participants performed worse on task balance in the task difficulty symmetry condition than in the task difficulty asymmetry condition. As such, increasing the difficulty of task selection surprisingly results in improving context-tracking, hence speaking for the separability of these two processes.

Note that participants did not perform the harder task more often than the easier task when the two tasks differed in difficulty, which is contrary to previous studies (Liefooghe et al., 2010; Millington et al., 2013; Weaver & Arrington, 2010; Yeung, 2010). One potential reason for this result is that the difference in difficulty between the two tasks in the task difficulty asymmetry condition may have not been strong enough for participants, as they were both perceptual tasks and were not strongly different in terms of working memory demands as in previous adult studies. But, more broadly, the effect of task difficulty (a)symmetry conditions on accuracy and RTs, as well as the lack of effect of these conditions on goal identification indices further suggest that task performance and goal identification tap different processes.

Another result was that *p*(switch) unexpectedly varied across age groups, with older children showing a higher *p*(switch). This pattern may be due to the fact that older children used more the 'Switch Only' strategy than other strategies and showed less variation in strategy use than younger children (see Supplemental Material, III). This suggests that *p*(switch) may be more informative about VTS performance in older children and adults than in younger children, the two former age groups showed less variability in the strategies used.

4. General discussion

We hypothesised that context-tracking and task selection are two inter-related key processes ensuring goal identification in situations necessitating self-directed control engagement: the information provided by context-tracking must be used to implement task selection, and conversely context-tracking requires updating contextual information once task selection has been implemented. So far, research on self-directed control has focused on task selection (e.g., Mittelstädt et al., 2018) whereas research on externally-driven tasks has examined context monitoring of cues (e.g., Hadley, Acluche, & Chevalier, 2020; Schuch, Dignath, Steinhauser, & Janczyk, 2019) but never addressed how context-tracking is achieved in the absence of cues and to what extent these processes may be related to each other. Results from Studies 1 and 2 indicated a dissociation between the effects of environmental support, which affects context-tracking, and task difficulty asymmetry, which makes task selection more difficult. Specifically, provision of environmental support enhanced task balance, whereas task difficulty asymmetry impaired task randomness, through more frequent engagement in systematic task sequences, but also improved context-tracking. These results suggest that task balance and task randomness respectively capture context-tracking and task selection. As varying the difficulty of one process does not necessarily negatively affect the other, our study brings the first evidence for some degree of independence between context-tracking and task selection (despite their conceptual inter-relatedness).

Following the dissociation between context-tracking and task selection, we observed that the effect of environmental support (Study 1) was most pronounced in younger participants, whereas the effect of task difficulty (a)symmetry (Study 2) did not interact with age. Therefore, although both context-tracking and task selection may contribute to self-directed control, context-tracking seems to drive developmental progress during childhood to a much greater extent than task selection. In other words, relative to adults, children disproportionately struggle to extract contextual information, however once this information has been extracted, they do not struggle more than adults to use it to identify the relevant task. Thus, our findings point out to distinct developmental trajectories, potentially reflecting more substantial age-related change in context-tracking than task selection, although further research is needed to examine the developmental course of these two processes in more detail.

An important question that follows from these findings is what drives better context-tracking with age. Working memory capacity increase during childhood (e.g., Camos &

Barrouillet, 2018) may play a prominent role. Working memory, which is a key component of cognitive control (Friedman & Miyake, 2017), is likely to support efficient context-tracking because this process requires maintaining contextual information without external aids and updating this information as a function of changes in the environment and/or past actions (i.e., previous task selections). Indeed, the slow development of working memory capacity during childhood and adolescence may explain why context-tracking remains challenging until late childhood. Specifically the cingulate cortex supports successful working memory engagement (Lenartowicz & McIntosh, 2005; Rushworth, Hadland, Gaffan, & Passingham, 2003), suggesting that context-tracking and working memory may be supported by common brain regions. Moreover, previous behavioural research has reported that children with atypical development causing working memory impairments show poorer performance on self-directed tasks than typically developing children, whereas this difference is attenuated in externally-driven tasks (Craig et al., 2016; White et al., 2009).

Interestingly, in Studies 1 and 2, children used systematic strategies consisting of repeating the same task or in switching tasks on every trial, which is in line with a previous study (Frick et al., 2019). These strategies may be a way for them to ease context-tracking demands, as they only require keeping track of the task performed on the immediately preceding trial. These strategies also facilitate task selection, but at the cost of reduced randomness. Further, younger children showed substantial variability in the types of strategy they used, more so than older children and adults. Although we did not measure working memory capacity, the types of strategy that children used may relate to individual differences in working memory capacity, as has been previously shown in a different task-switching paradigm at age 5 (Dauvier et al., 2012). For instance, children with the poorest working memory capacities may have used the strategy of repeating always the same task, as this pattern does not require strong maintenance of previous tasks and contextual information updating while also dropping switching demands. Conversely, children with higher working memory capacities may have used more demanding strategies such as switching on every two trials or may have used less strategies overall. Indeed, their working memory capacities might have been strong enough to manage the higher costs of context-tracking without external aids. Nevertheless, this claim remains a speculation at this stage, as we did not test working memory capacity, however, it offers an interesting venue for future research to explore the link between working memory capacities and context-tracking.

In addition to working memory, age-related gains in context-tracking may relate to increasing abstract representation capacity, which has been argued to support successful self-directed control development (Snyder & Munakata, 2010, 2013). This capacity allows the formation and maintenance of task representations, which may be critical to context-tracking. More specifically, previous studies on self-directed control development have typically used fluency tasks, in which children were asked to name as many items from a particular category (e.g., animals) as possible in a short amount of time. Younger children were found to struggle to form short clusters of items from the same sub-category (e.g., lion, tiger, zebra etc.) but also to repeat the same items throughout the task (Snyder & Munakata, 2010, 2013). While this behaviour may be explained by failure to form abstract representations of different categories and sub-categories, this might be also due to difficulties with context-tracking, namely with manipulating these abstract representations to keep track of which items have already been chosen and from which specific sub-category. However, at this point, it remains an open question whether gains in context-tracking relate to increasingly abstract representations and/or greater working memory capacity with age. This question should be directly addressed in future research.

Finally, Studies 1 and 2 consistently showed that even younger children had very little difficulty in switching between tasks, as evidenced by their frequent use of the ‘Switch Only’ strategy, as previously reported in the VTS paradigm (Frick et al., 2019). Of particular interest, recent research using externally-driven tasks has shown that that switch costs (i.e., the costs associated with task switching) do not vary with age whereas mixing costs (i.e., the costs associated with goal identification) decrease with age (Chevalier et al., 2018; Peng, Kirkham, & Mareschal, 2018). Taken together, our study adds to the growing body of evidence that goal identification may be a greater source of difficulty than switching *per se* in cognitive control development (Broeker et al., 2018; Chevalier, 2015).

To conclude, both context-tracking and task selection contribute to self-directed control performance, but age-related gains during children are mostly driven by progress in context-tracking. Future research will need to clarify what drives increasingly efficient context-tracking with age, paying special attention to increasing working memory capacities and/or abstract representations. Answering these questions may also help develop efficient interventions aimed at promoting autonomous behaviours in children. Moreover, the dissociation between context tracking and task selection opens up the possibility that these two processes may be supported by distinct brain substrates. Past research has largely highlighted that different areas of the cingulate cortex (e.g., anterior, rostral, dorsal), alongside with the dorsolateral prefrontal cortex (dlPFC), are involved in goal identification processes in self-directed control (Forstmann, Brass, Koch, & von Cramon, 2006; Holroyd & McClure, 2015; Umemoto & Holroyd, 2016; Wisniewski, Reverberi, Tusche, & Haynes, 2015), but these studies did not disentangle context-tracking from task selection. As such, considering the distinction between context tracking and task selection may help disentangle the contribution of these brain regions to self-directed control and its development across childhood.

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Supplemental Material: Analyses of accuracy and log RTs for Study 1 and Study 2

I. Study 1 – Accuracy and RTs

Data processing and analyses

Task performance was indexed by accuracy and response times (RTs) for each trial type, which allowed estimating mixing costs (contrasting between single task trials and task repetition trials) and switch costs (contrasting between task repetition trials and task switch trials). Task mixing costs index the difficulty of selecting the relevant task when tasks are mixed and task switching costs index the difficulty of switching from one task to another (Rubin & Meiran, 2005). Analyses were performed after discarding the first trial of each block. RTs were log-transformed (to correct for skewness; Meiran, 1996) and for the course of their analyses, incorrect responses or correct responses following an incorrect response were trimmed, trials following the elf appearance and trials under 200 ms or greater than 3 standard deviations above the mean of each participant (computed separately for each trial type) or 10,000 ms were trimmed.

Accuracy was analysed with a Generalized Linear Mixed Model (GLMM) and averaged RTs were analysed using a Linear Mixed Model. Models were fit in R version 4.0.2 (R Core Team, 2020) using the *lme4* package (Bates, Mächler, & Bolker, 2015) with age group (5-6 years, 9-10 years, adults), environmental support condition (environmental support, no environmental support) and trial type (single task, task repetition, task switch) as fixed effects and the variable Participant as a random effect. On glmer/lmer outputs, we performed mixed model ANOVA tables via Likelihood Ratio Test using the *afex* package (Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020). Tukey's post-hoc tests were used for pairwise comparisons when there were multiplicity issues using the *emmeans* package (Lenth, 2020) and estimated marginal means (EMMs) are reported. Plots of the results were obtained using the *ggeffects* and *ggplot2* packages (Hadley, 2016; Lüdecke, 2018).

Accuracy rates

Effects of age group, $\chi^2 = 65.90$, $df = 2$, $p < .001$, environmental support condition, $\chi^2 = 14.25$, $df = 1$, $p < .001$ and trial type, $\chi^2 = 97.39$, $df = 2$, $p < .001$, were observed (Figure 1). 5-6 year-olds were less accurate than 9-10 year-olds and adults ($M_{\text{5-6 year-olds}} = 89$ *vs.* $M_{\text{9-10 year-olds}} = .96$ *vs.* $M_{\text{adults}} = .97$; $ps < .001$), whereas the two latter age groups did not differ, $p = .175$. Participants were less accurate in the environmental support condition than in the no environmental support condition ($M_{\text{no environmental support condition}} = .94$ vs. $M_{\text{environmental support condition}} = .95$). Accuracy on single task trials were lower than on task repetition trials ($M_{\text{single task trials}} = .97$ *vs.* $M_{\text{task repetition trials}} = .93$; $p < .001$), and task repetition and task switch trials did not differ, $p = 1$, hence revealing significant mixing costs but non-significant switch costs overall.

Age group and trial type interacted, $\chi^2 = 24.56$, $df = 4$, $p < .001$, revealing that although both age groups showed significant mixing costs (5-6 year-old: $M_{\text{single task trials}} = .95$ *vs.* $M_{\text{task repetition trials}} = .86$; 9-10 years-old: $M_{\text{single task trials}} = .97$ *vs.* $M_{\text{task repetition trials}} = .85$; Adults: $M_{\text{single task trials}} = .98$ *vs.* $M_{\text{task repetition trials}} = .96$; $ps < .001$), switch costs were marginally significant for younger children ($M_{\text{task switch trials}} = .84$; $p = .092$) but not for other age groups, $ps > .297$.

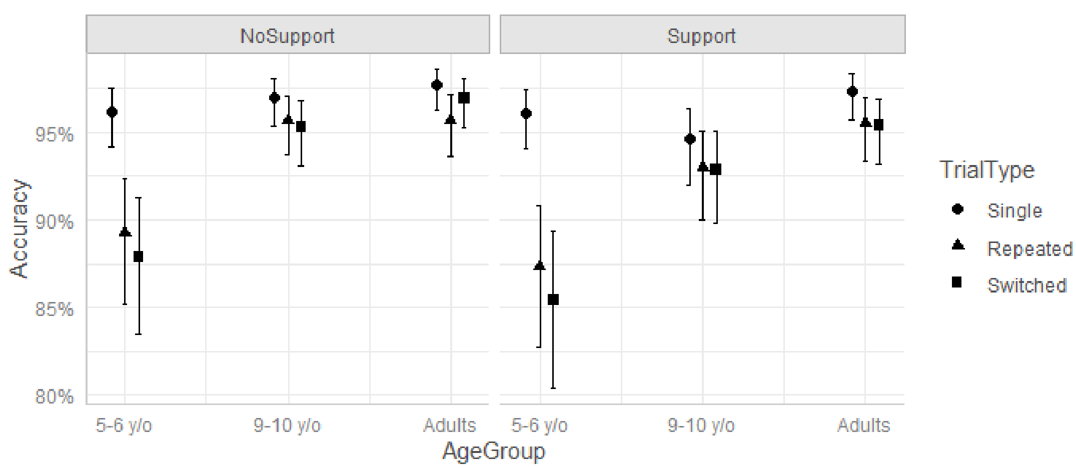
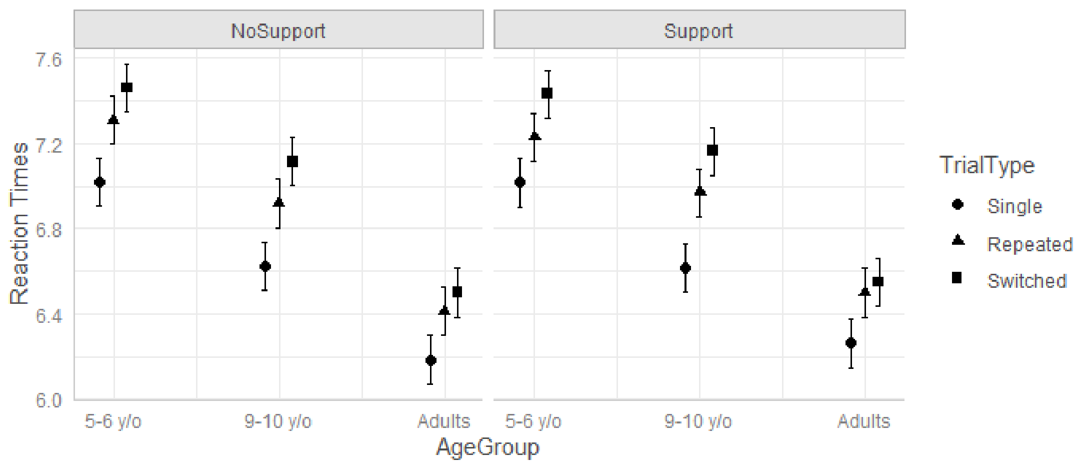


Figure 1. Accuracy as a function of age group (5-6 year-olds, 9-10 year-olds, adults) environmental support condition (environmental support, no environmental support) and trial type (single task, task repetition, task switch). Mixing costs were significant and switch costs were not significant for all age groups, although the latter approached the significance level for 5-6 year-olds.

Log RTs

Effects of age group, $\chi^2 = 100.88$, $df = 2$, $p < .001$, trial type, $\chi^2 = 237.79$, $df = 2$, $p < .001$, but not of environmental support condition, $p = .264$, were observed. RTs significantly decreased across all age groups ($M_{\text{5-6 year-olds}} = 7.24$ ln ms *vs.* $M_{\text{9-10 year-olds}} = 6.90$ ln ms *vs.* $M_{\text{adults}} = 6.40$ ln ms; $ps < .001$). RTs were lower on single task trials than on task repetition trials, and lower on task repetition trials than task switch trials ($M_{\text{single task trials}} = 6.62$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.89$ ln ms vs $M_{\text{task switch trials}} = 7.04$ ln ms; $ps < .001$), revealing significant mixing and switch costs.

Age group and trial type significantly interacted, $\chi^2 = 14.61$, $df = 4$, $p = .006$, revealing that adults did not show significant switch costs, $p = .246$, but significant mixing costs ($M_{\text{single task trials}} = 6.22$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.46$ ln ms; $p < .001$). Children showed both significant mixing and switch costs contrary to children (5-6 year-olds: $M_{\text{single task trials}} = 7.02$ *vs.* $M_{\text{task repetition trials}} = 7.27$ ln ms *vs.* $M_{\text{task switch trials}} = 7.45$ ln ms; 9-10 year-olds: $M_{\text{single task trials}} = 6.62$ *vs.* $M_{\text{task repetition trials}} = 6.94$ ln ms *vs.* $M_{\text{task switch trials}} = 7.14$ ln ms; $ps < .001$).



Log RTs as a function of age group (5-6 year-olds, 9-10 year-olds, adults) environmental support condition (environmental support, no environmental support) and trial type (single task, task repetition, task switch). Significant mixing costs were observed for all age groups but switch costs were observed for children only.

II. Study 2 – Accuracy and RTs

Data processing and analyses

As Study 1, these analyses were performed after discarding the first trial of each block. Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). Only RTs for correct trials preceded by correct trials were kept. RTs on trials following the appearance of the elf were also removed as their latencies were longer than on normal trials. Finally, RTs were trimmed out if they were under 200 ms, to account for accidental button presses, or greater than 3 standard deviations above the mean of each participant (computed separately for trials from single blocks, and task repetition and task switch trials from mixed blocks) or 10,000 ms.

Analyses were similar to Study 1 expect that the experimental condition was task difficulty (a)symmetry (task difficulty symmetry, task difficulty asymmetry).

Accuracy rates

On accuracy, there were main effects of age group, $\chi^2 = 19.56$, $df = 2$, $p < .001$, task difficulty (a)symmetry condition, $\chi^2 = 64.16$, $df = 1$, $p < .001$, and trial type, $\chi^2 = 42.29$, $df = 2$, $p < .001$ (Figure 3). 5-6 year-olds and 9-10 years-old were significantly less accurate than adults ($M_{\text{5-6 year-olds}} = .92$ *vs.* $M_{\text{9-10 year-olds}} = .93$ vs. $M_{\text{adults}} = .97$; $ps < .001$), but they did not differ from each other, $p = .872$. Accuracy was lower in the task difficulty asymmetry condition than in the task difficulty symmetry condition ($M_{\text{task difficulty symmetry condition}} = .96$ vs. $M_{\text{task difficulty asymmetry condition}} = .93$) and lower on task repetition trials than on single task trials but no difference was observed between task repetition trials and task switch trials ($M_{\text{single task trials}} = .96$ *vs.* $M_{\text{task repetition trials}} = .94$ *vs.* $M_{\text{task switch trials}} = .93$; $ps < .001$ and $p = .640$), hence revealing significant mixing costs but no significant switch costs overall.

These effects were qualified by a three-way interaction between these factors, $\chi^2 = 9.52$, $df = 4$, $p = .049$, revealing that 9-10 year-olds showed no significant switch costs in all condition, $ps > .683$, no significant mixing costs in the task difficulty symmetry condition, $p = .174$, but significant mixing costs in the task difficulty asymmetry condition ($M_{\text{single task trials}} = .95$ *vs.* $M_{\text{task repetition trials}} = .89$; $p < .001$). 5-6 year-olds showed significant mixing costs in all conditions (task difficulty symmetry: $M_{\text{single task trials}} = .96$ *vs.* $M_{\text{task repetition trials}} = .90$; task difficulty asymmetry: $M_{\text{single task trials}} = .95$ *vs.* $M_{\text{task repetition trials}} = .92$; $ps < .014$), but no significant switch costs, $ps > .121$. Adults showed no significant mixing or switch costs, $ps > .082$.

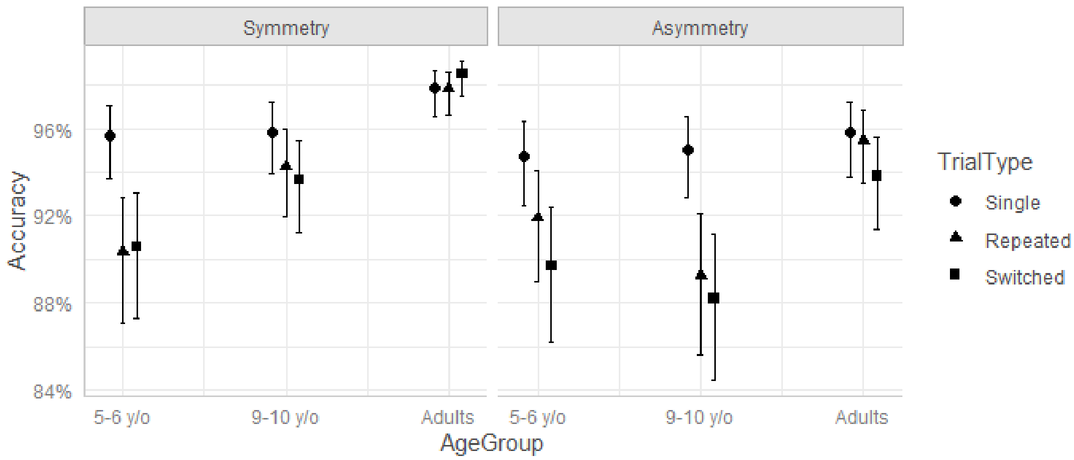


Figure 3. Accuracy as a function of age group (5-6 year-olds, 9-10 year-olds, adults), task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry) and trial type (single task, task repetition, task switch). 5-6 year-olds showed significant mixing costs but no significant switch costs in all conditions. 9-10 year-olds showed significant mixing costs in the task difficulty asymmetry condition only. Adults showed no mixing and switch costs.

Log RTs

On log RTs, the analysis revealed main effects of age group, $\chi^2 = 114.19$, $df = 2$, $p < .001$, task difficulty (a)symmetry condition, $\chi^2 = 147.71$, $df = 1$, $p < .001$, and trial type, $\chi^2 = 310.68$ $df = 2$, $p < .001$, but no significant interactions, *ps* > .260. 5-6 year-olds were significantly slower than 9-10 year-olds who were slower than adults ($M_{\text{5-6 year-olds}} = 7.37$ ln ms *vs.* $M_{\text{9-10 year-olds}} = 6.87$ ln ms vs. $M_{\text{adults}} = 6.49$ ln ms; *ps* < .001). Moreover, participants were significantly slower in the task difficulty asymmetry condition than in task difficulty symmetry condition ($M_{\text{task difficulty symmetry condition}} = 6.81$ ln ms vs. $M_{\text{task difficulty asymmetry condition}} = 7.01$ ln ms. Finally, participant showed significant mixing and switch costs ($M_{\text{single}} = 6.69$ ln ms *vs.* $M_{\text{task repetition}} = 6.95$ ln ms *vs.* $M_{\text{task switch}} = 7.09$ ln ms; *ps* < .001).

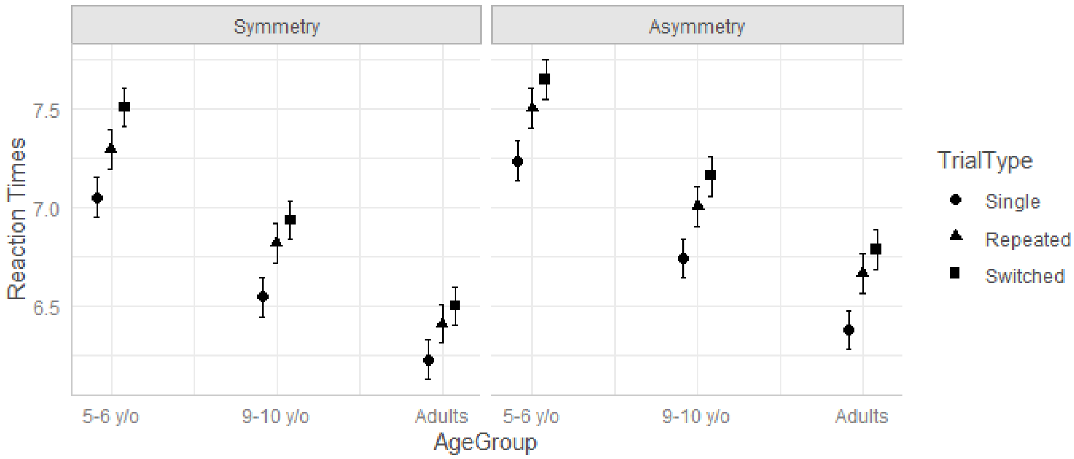


Figure 4. Log RTs as a function of age group (5-6 year-olds, 9-10 year-olds, adults), task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry) and trial type (single task, task repetition, task switch). Log RTs decreased with age, were greater in the task difficulty asymmetry condition than in the task symmetry condition and participants showed both significant mixing and switch costs.

III. Study 2 – Complementary analyses with a mixed ANOVA on task randomness

The analysis revealed main effects of age group, $F(2, 87) = 13.45$, $p < .001$, $\eta^2_p = .236$, task difficulty (a)symmetry condition, $F(1, 87) = 5.60$, $p = .020$, $\eta^2_p = .060$, and strategy type, $F(4, 348) = 19.11$, $p < .001$, $\eta^2_p = .180$, on strategy occurrences. 5-6 year-olds used significantly more strategies than 9-10 year-olds, who used significantly more strategies than adults ($M_{\text{5-6 year-olds}} = .58$ *vs.* $M_{\text{9-10 year-olds}} = .40$ *vs.* $M_{\text{adults}} = .24$; *ps* < .044). Participants used significantly more strategy in the task difficulty asymmetry condition than in the task symmetry condition ($M_{\text{task difficulty symmetry condition}} = .45$ *vs.* $M_{\text{task difficulty asymmetry condition}} = .36$), and used more the ‘Switch Only’ and ‘One Repetition and Switch’ strategies than other strategies ($M_{\text{Repetition Only}}$ = .36 *vs.* $M_{\text{Switch Only}}$ = .79 *vs.* $M_{\text{One Repetition and Switch}}$ = .64 *vs.* $M_{\text{Two Repetitions and Switch}}$ = .20 *vs.* $M_{\text{Three Repetitions and Switch}}$ = .03; *ps* < .049), with no difference between these two strategies, *p* = .571.

Age group significantly interacted with strategy type, $F(8, 348) = 3.08$, $p = .009$, η^2_p = .066 (Figure 5). 5-6 year-olds used significantly more the ‘Repeat Only’ strategy than other age groups ($M_{\text{5-6 year-olds}}$ = .73 *vs.* $M_{\text{9-10 year-olds}}$ = .13 *vs.* M_{adults} = .22; *ps* < .007), with no difference between 9-10 year-olds and adults, *p* = .875. 5-6 year-olds and 9-10 year-olds used more the ‘Switch Only’ strategy than adults ($M_{\text{5-6 year-olds}}$ = 1.08 *vs.* $M_{\text{9-10 year-olds}}$ = .97 *vs.* M_{adults} = .32; *ps* < .001), with no difference between children, *p* = .770. 5-6 year-olds used more the ‘One Repetition and Switch’ strategy than adults but not than 9-10 year-olds ($M_{\text{5-6 year-olds}}$ = .82 *vs.* $M_{\text{9-10 year-olds}}$ = .72 *vs.* M_{adults} = .38; *p* = .029 and *p* = 825) with no difference between the two latter age groups, *p* = .121. No other differences between age groups and strategy types were observed, *ps* > .875. 5-6 year-olds used similarly the ‘Repetition Only’, ‘Switch Only’ and ‘One Repetition and Switch’ strategy, *ps* > .265, but more than other strategies ($M_{\text{One Repetition and Switch}}$ = .82 *vs.* $M_{\text{Two Repetitions and Switch}}$ = .18 *vs.* $M_{\text{Three Repetitions and Switch}}$ = .07; *ps* < .016). 9-10 year-olds used more the ‘Switch Only’ strategy than the ‘Repetition Only’ strategy, *p* < .001, but similarly the ‘Switch Only’ strategy and the ‘One Repetition and Switch’ strategy, *p* = .607, and more the ‘One Repetition and Switch’ strategy than the ‘Repeat Only’ strategy, *p* = .008. Adults used all strategies similarly, *ps* > .183.

Task difficulty (a)symmetry condition significantly interacted with strategy type, $F(4, 348) = 3.02$, $p = .041$, η^2_p = .033, revealing that the ‘Switch Only’ strategy was more used in the task asymmetry condition than in the task symmetry condition ($M_{\text{task symmetry condition}}$ = .57 *vs.* $M_{\text{task asymmetry condition}}$ = .1.01; *p* < .001), whereas no differences between task difficulty conditions were observed for other strategies, *ps* > .488.

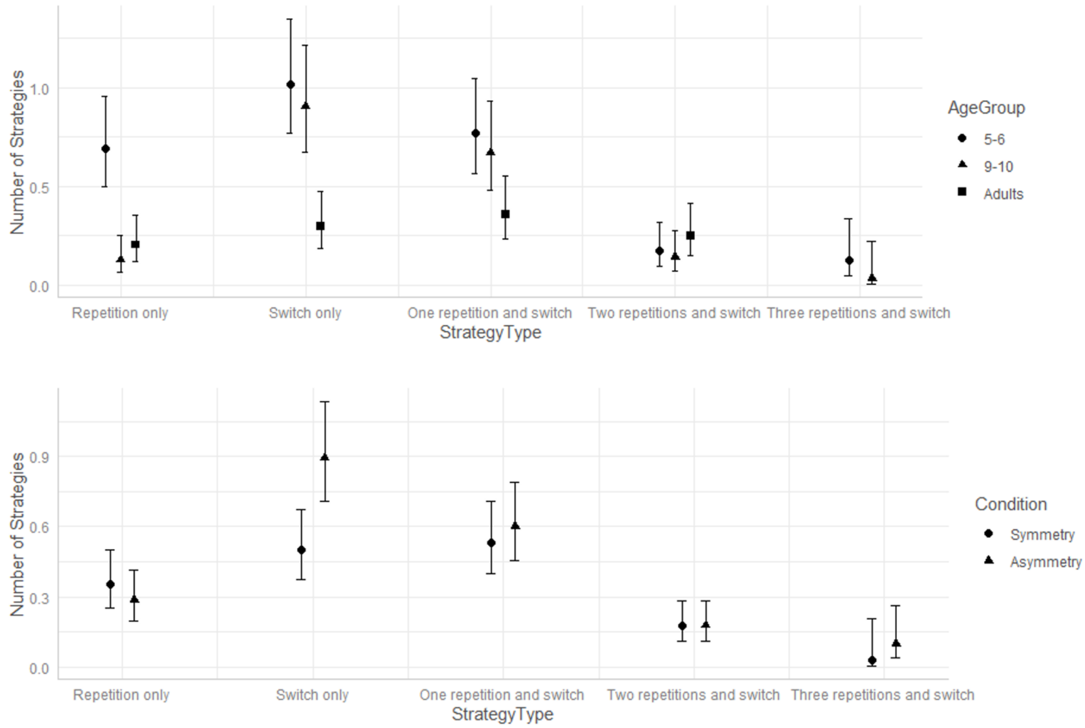


Figure 5. Number of strategy used as a function of the type of strategies (Repeat Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetitions and Switch) and age group (5-6 year-olds, 9-10 year-olds, adults; top figure), and as a function of the type of strategies and task difficulty (a)symmetry (task difficulty symmetry, task difficulty asymmetry; bottom figure). 5-6 year-olds and 9-10 year-olds used significantly more strategies than adults. The ‘Switch Only’ strategy was more used in the task difficulty asymmetry condition than in the task difficulty symmetry condition.

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Chapter 5: Discussion and conclusion

Developing autonomous behaviours is critical in children's lives, especially in school situations where the instructions given by the teachers become less externally-driven and require children to self-directly engage cognitive control to achieve goals. For instance, when moving up grades, children are increasingly expected to decide by themselves which relevant part of the course should be studied and how long in order to successfully prepare for an exam. Understanding how a self-directed form of control develops and what are the underlying cognitive processes driving this development is therefore crucial to develop efficient training programmes promoting this form of control, and later academic achievement.

To this aim, in this dissertation, I presented three developmental studies with the objective to disentangle the processes at play in self-directed control development (Chapter 2). I then focused on the process of task selection to investigate how it develops across childhood using a paradigm that specifically targets this process (Chapter 3). This investigation led me to better understand the processes underlying goal identification in self-directed control, namely context-tracking and task selection, and how they contribute to the development of this form of control during childhood (Chapter 4). In the following, I first discuss the novel methodological and conceptual achievements of this dissertation to investigate self-directed control in childhood. I then move on the main findings coming from the studies carried out in these different chapters, and propose a tentative theoretical model of self-directed control development. Following this, I address some limitations which, hopefully, offer interesting venues for future research, before closing this dissertation by a short summary.

1 Challenge of investigating self-directed control in childhood

Understanding self-directed control remains a challenge. In psychological research, and more particularly when examining cognitive control, participants are almost always driven by clear instructions before starting the task, cues throughout the task, or reminders at some point during the task (e.g., Stroop task or cued task-switching paradigm; Meiran, 1996; Stroop, 1935). In comparison, few studies have been carried out with tasks offering less guidance. Wilson, Alderman, Burgess, Emslie, and Evans (1996) have developed the Behavioural Assessment of the Dysexecutive Syndrome (BADS) in which two tasks (Key Search task, Six Elements task) tap self-directed control, and this battery has been adapted for use with children (Emslie, Wilson, V, Nimmo-Smith, & Wilson, 2004), but the minimum age required for this battery is 8 years-old. Similarly, the Verbal Fluency assesses self-directed control (Troyer et al., 1997), but is not informative in children below 7 years-old due to their low linguistic abilities. Finally, another candidate is the alternating-runs task-switching paradigm (Rogers & Monsell, 1995), which has been used with children aged 5-years-old (e.g., Dauvier et al., 2012), but given that the instructions of the alternating rule is given prior the start of the experiment, this paradigm nevertheless offers some guidance critically for task performance, and therefore remains partially externally-driven. As such, there was a real need to develop a task that exclusively relies on self-directed control and is appropriate for use with very young children.

In Chapters 3 and 4, I adapted the gold-standard paradigm of self-directed used with adults, VTS (Arrington & Logan, 2004), which specifically targets goal identification with a particular focus on task selection, measured by the amount of task switches made in comparison to task repetition, namely *p*(switch). In my paradigm, the instructions of performing the two tasks equally often and in a random manner was explained to the children as putting the same number of toys in two bags and tricking a thief elf. As described in Chapter 3, even younger children performed well during the practice revealing that these instructions were appropriate. Further, I extended the variable of interest, initially only *p*(switch), to other variable of interests which were how well the two tasks were performed equally (task balance) and whether task choice was really random as evidenced by different patterns of possible strategies (task randomness) in order to get finer analyses of goal identification processes at play in VTS.

Moreover, due to the fact that this child-friendly paradigm is a task-switching paradigm, it also offers the possibility for experimental manipulations. In Chapters 3 and 4, I manipulated the time between the response and stimulus onset, environmental support and task difficulty, the latter two offering insight about the two sub-processes of goal identification, which have so far always been confounded. Of particular importance, further modifications could be applied to our paradigm such as modifying the general instructions (e.g., removing one and/or both instructions) to investigate how children behave, removing the appearance of the thief elf which could be act as a reminder throughout the task, using more than two tasks, and so forth. Consequently, in addition to offering a better insight of goal identification processes in self-directed control, I offer here a novel tool that can be used in future studies to replicate and/or refine our understanding of this form of control.

2 A tentative theoretical model of self-directed control development based on goal identification

2.1 Goal identification more than switching *per se* is the main difficulty in self-directed control development

In this dissertation, I investigated cognitive control development using task-switching paradigms. These paradigms are associated with mixing (or global) and switch (or local) costs as regards to accuracy and RTs. Recall that mixing costs capture a critical performance drop associated with repeating a task in blocks where it is mixed with another task (i.e., high task uncertainty; task repetition trials in mixed blocks), relative to repeating a task in a block where the same task is always relevant (i.e., low task uncertainty; trials from single-task blocks). Switch costs correspond to the additional performance drop on trials where participants actually need to switch tasks relative to task repeat trials within mixed-task blocks Peng et al. (2018); Rubin and Meiran (2005). As task uncertainty is high on both switch and repeat trials within mixed blocks, mixing costs may mostly reflect the difficulty of goal identification (e.g., Kikumoto & Mayr, 2017). Further, as task uncertainty may be similar on both switch and repeat trials within mixed blocks (at least when both trial types are equally frequent), switch costs may mostly reflect the greater difficulty of executing a task when one needs to reorient attention to information that has been previously ignored (e.g., Courtemanche et al., 2019).

In externally-driven control, numerous studies have examined accuracy and RTs mixing and switch costs across development. Studies from more than a decade ago have examined mixing costs in children and showed that these costs decrease from 7 years-old onwards (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Kray, Eber, & Karbach, 2008; Reimers & Maylor, 2005), suggesting age-related progress in goal identification throughout the lifespan. Conversely, findings regarding switch costs have yielded mixed conclusions. Indeed, some research has reported a significant decrease with age regarding these costs (e.g., Cepeda et al., 2001; Crone, Bunge, Van Der Molen, & Ridderinkhof, 2006; Davidson, Amso, Anderson, & Diamond, 2006) whereas other research has observed no changes with age (e.g., Dibbets & Jolles, 2006; Ellefson et al., 2006; Reimers & Maylor, 2005). However, recent research investigating mixing and switch costs from early childhood has shown that the magnitude of improvements with age is more pronounced for mixing costs than for switch costs (Chevalier, Dauvier, & Blaye, 2018; Peng et al., 2018). This suggests that difficulties for children when engaging externally-driven cognitive control, and more particularly in task-switching situations, rely on goal identification to a greater extent than on difficulties related to switching *per se*.

In line with this previous research on externally-driven control, I observed that in self-directed situations, task selection, a key process of goal identification, is mastered later in development than task execution, although these two processes are somehow related regarding performance costs as a function of the self-directedness of the task (Chapter 2). But critically, I also reported that children as young as 5 years-old have little difficulties engaging switching behaviours (Chapters 3 and 4). Indeed, in the voluntary task-switching paradigm, 5 year-olds often relied on a predictable strategy that consisted of switching tasks on every trial, indicating that they can easily redirect their attention to activate a new task different from the task just performed. However, these children, as well as older children aged 9- to 10-years-old, struggled to select the appropriate task in order to perform the two tasks equally often (task balance) and in a random order (task randomness), hence revealing that difficulties do not rely on activating a new task, but rather selecting which task is relevant. Moreover, as regards accuracy, no switch costs were observed in children and adults whereas mixing costs were observed only in children (Chapters 3 and 4). Taken together, this indicates that goal identification, much more than switching *per se*, is the main source of difficulty in the development of self-directed cognitive control engagement, but more broadly, this extends this claim to all forms of cognitive control.

2.2 The sub-processes underlying self-directed control development: The premises of a theoretical model

As stated in the previous paragraph, goal identification is key in self-directed control development. In particular, based on these findings, I propose a tentative theoretical model of the underlying processes of goal identification in self-directed control development. In this theoretical model (Figure 1), goals are self-directedly identified through two sub-processes, which are context-tracking and task selection (Chapter 4).

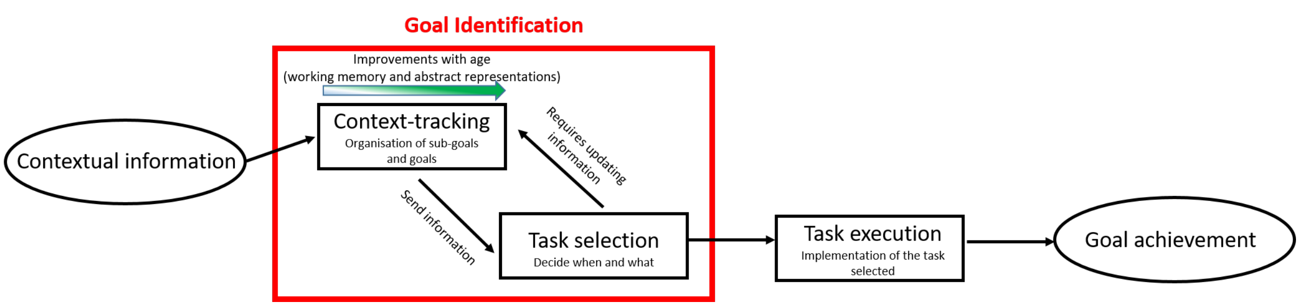

Figure 1: Theoretical model of the underlying processes of goal identification in self-directed and its development with age.

More specifically, contextual information is treated directly by the context-tracking process for which the first role is to store and monitor this information. However, contextual information is also influenced by changes in task demands or goals and is influenced by past actions. In particular, attainment of a specific goal (e.g., prepare dinner) may require a series of sub-goals (e.g., cut ingredients, boil water, etc.). Therefore, the second role of context-tracking is to keep track of contextual information including where one stands in a hierarchy of sub-goals and goals, or cues suggesting that a new goal should be pursued. The second cognitive process, task selection, consists in using this contextual information to determine when and what behaviour should be engaged in order to achieve sub-goals and goals. However, the relation between context-tracking and task selection is bi-directional. Indeed, although context-tracking guides task selection by providing information about sub-goals and goals, task selection may also influence the content of this information, as this information must be updated after a task has been selected and executed (i.e., once a task has been selected, this selection should be considered when one keeps track of the context).

Results from Chapter 4 indicated that despite their conceptual inter-relatedness, context-tracking and task selection show some degree of independence. Indeed, varying the difficulty of one process does not systematically affect the other process. Further, progress in goal identification in self-directed control throughout development appears to be mostly due to improvements in context-tracking rather than task selection, as providing environmental support improves the implementation of the first process in children, but not in adults. Context-tracking is likely to be supported by increasing working memory and abstract representation capacities (e.g., Cowan, 2014; Snyder & Munakata, 2013), which allow for adaptive storage and manipulation of the information needed for the task selection process. In particular, better working memory performance with age is achieved by increasing capacities for abstractedly refreshing information held in memory (Camos & Barrouillet, 2011; Camos, Mora, & Oberauer, 2011; Souza, Rerko, & Oberauer, 2015). Such a refreshing process may be key for context-tracking involving micro-switches of attention between the tasks done and the new task that needs to be selected in order to achieve a goal. However, how working memory and abstract representations precisely support efficient context-tracking remains to be investigated and offer an interesting venue for future research.

Furthermore, such dissociation between context-tracking and task selection does not appear as a surprise as previous studies have identified that several areas of the prefrontal cortex and cingulate cortex are activated when identifying goals in self-directed control (Forstmann et al., 2006; Holroyd & McClure, 2015; Umemoto & Holroyd, 2016; Wisniewski, Reverberi, Tusche, & Haynes, 2015). But interestingly, this distinction may offer insights on how these brain regions support self-directed control. For instance, if context-tracking taps on working memory and abstract representations capacities, one may expect this process to involve more activation of the right dorso-lateral prefrontal cortex (DLPFC; e.g., Cabeza, Anderson, Locantore, & McIntosh, 2002; Christophel, Klink, Spitzer, Roelfsema, & Haynes, 2017; Funahashi, 2017) and rely on increasing fronto-parietal connectivity (Sauseng, Klimesch, Schabus, & Doppelmayr, 2005). Conversely, task selection may involve more anterior regions such as the dorsal anterior cingulate cortex (dACC; e.g., Wisniewski et al., 2015). Of particular importance, involvement of brain areas in cognitive control becomes specialised during childhood with a shift from diffuse to focal prefrontal activity as well as a progressive segregation and integration of fronto-parietal networks (e.g., Durston et al., 2006; Fair et al., 2009), which supports increasingly successful cognitive control engagement, and therefore might also be key for self-directed control.

At this stage, this theoretical model is at its premises. Indeed, it is still unclear how context-tracking organises the hierarchy of sub-goals and goals, similarly to the Supervisory Attentional System which monitors the Contention Scheduling (i.e., context-tracking) in order to activate or suppress schematas when engaging control, according to the seminal model of Norman and Shallice (1986), and how task selection uses this information to decide when and what behaviour should be engaged. For instance, when children are provided with environmental support (Chapter 4, Study 1), although they more ably perform the two tasks equally often, they still struggle to select them randomly. As such, it might also be that the difficulties for children are to use the information from context-tracking before passing it on to task selection, but at this stage this remains speculative. One way to address this question would be to use a version of the voluntary task-switching paradigm similar to Chapter 4 (Study 1) contrasting between providing environmental support or not and in which a cue would signal to the children that the thief elf is about to steal a toy. If younger children struggle to use the information coming from context-tracking, then we should not observe any differences between the two environmental support conditions, suggesting that even when context-tracking is facilitated, using this information remains difficult in order to select the appropriate task.

Moreover, while working memory and abstract representation capacities may be crucial for context-tracking specifically, it is unknown to what extent and how inhibitory processes are involved either in context-tracking or task selection, or both. For instance, it is plausible that sub-goals or goals are no longer pursued based on the information provided by context-tracking, but that the decision of abandoning these sub-goals and goals is taken when one has to select a task. As such, inhibition processes may be a retroactive break only activated during task selection, which forces context-tracking to update the sub-goals and goals. This question is an exciting venue for future research attempting to identify which executive processes are at play during goal identification.

3 Limitations and directions for future studies

3.1 Use of physiological measures in self-directed control development

In Chapter 3, I showed that different preparation durations, one favouring the use of proactive control (long preparation time, 1,500 ms) and another supposedly forcing the use of reactive control (short preparation time, 100 ms), did not influence self-directed control. However, despite these different preparation times, participants had a time interval of 500 ms between their responses and the start of the preparation time before stimulus onset. This has potentially resulted in participants having enough time to prepare for the next trial right after their responses. As such, my study did not allow us to conclude firmly whether or not younger children were biased towards a reactive form of control whereas conversely older participants used a proactive form of control. Further, results from Chapter 4 indicated that even older children, who are likely to rely on proactive control, had difficulties with goal identification, suggesting that proactive control is not synonymous of successful self-directed control as argued in the adult literature. Recall that according to Arrington et al. (2014), one needs to have enough time to prepare in advance for the upcoming trial in order to select adaptively the appropriate task (i.e., representativeness heuristic). One way to directly address this question is to combine physiological measures such event-related potentials (ERPs) and/or pupillometric measures to behavioural investigations.

Examinations of ERPs have revealed that different neuro-cognitive markers are associated with task preparedness in self-directed control. Specifically, before stimulus onset, a preparatory medial frontal modulation has been found to be associated with voluntary task selection (Forstmann, Ridderinkhof, Kaiser, & Bledowski, 2007). Studies using ERPs have shown that task preparation is associated with a slowly developing negative wave across frontal sites (i.e., contingent negative variation, CNV; Falkenstein, Hoormann, Hohnsbein, & Kleinsorge, 2003; Hoofs, Princen, Poljac, Stolk, & Poljac, 2018; Poljac & Yeung, 2014). Interestingly, the CNV seems to reflect intentional task preparation in self-directed control, being stronger in task switch trials (Kang, DiRaddo, Logan, & Woodman, 2014; Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010), and more pronounced in fast responses (Lavric, Mizon, & Monsell, 2008; Poljac & Yeung, 2014). This suggests that trial types are differently prepared. Of particular interest, a recent study has reported that the CNV is attenuated in individuals with autistic traits but not control participants (Hoofs et al., 2018), confirming difficulties of the former group in behavioural studies on self-directed control (e.g., Poljac, Hoofs, Princen, & Poljac, 2017; White et al., 2009), potentially due to a lack of efficient task preparation before stimulus onset or an efficient use of proactive control.

This result offers an important venue for future ERPs research in self-directed control development as examining the CNV in children can shed light on whether or not they efficiently prepare or not their responses in advance. Indeed, as stated previously, in Chapter 3, participants had enough time to prepare for the next trial as the stimulus to response interval was of 600 ms. Critically, previous studies have shown that the CNV is present 600 ms before the appearance of the stimulus (Hoofs et al., 2018; Poljac & Yeung, 2014), confirming that our study did not allow to conclude firmly whether or not younger children relied more on a reactive form of control whereas conversely older participants used a proactive form of control. Future research should examine the CNV in children and adults during self-directed control engagement with the expectation that the CNV would be attenuated in younger children as they tend to not prepare their responses in advance (Chevalier et al., 2015; Doebel et al., 2017) as compared to older participants.

Note that besides ERPs, further measures that could be of interest are pupillometry and blink rates acquired through eye-tracking. Pupil dilation can be used as an alternative or in addition to ERPs to examine the temporal dynamics of cognitive control and changes in cognitive demand and effort (Beatty, 1982; Chiew & Braver, 2013). Indeed, developmental research has shown that when engaging proactive control, greater pupil dilation before the onset of a stimulus is observed, whereas no such modulations are observed when reactive control is engaged (Chatham et al., 2009; Chevalier et al., 2015). Blink rates can be also used as a peripheral measure of dopamine which modulates fronto-striatal circuits supporting the maintenance of abstract goals and motivation to hierarchically organise and update of sub-goals and goals in relation to working memory allocation (Puig, Rose, Schmidt, & Freund, 2014; Westbrook & Braver, 2016).

As such, an interesting venue for future studies would be to combine ERPs and eye-tracking measures in order to try clarifying (1) whether reactive and proactive control do matter in successful goal identification in self-directed control and (2) whether when context-tracking and task selection are experimentally disentangled, this dissociation can be evidenced by blink rates (e.g., more voluntary blink rates when keeping track of the context than selecting the relevant task).

3.2 *P*(switch) and cognitive fatigue

One of the main findings from Chapters 2 and 3 is that *p*(switch) did not strongly vary across age groups and the different experimental conditions. Note that *p*(switch) was significantly lower for younger children when little time preparation between the response and the stimulus was available (Chapter 3) and that *p*(switch) was higher for older children in Study 2 (Chapter 4). But overall, children and adults showed similar *p*(switch), challenging the supposedly reversed U-shape pattern for this measure with age (e.g., Poljac et al., 2018; Terry & Sliwinski, 2012). Moreover, although adults showed a small repetition bias in Chapters 3 and 4, this was above the expected value of .44

and therefore not significantly different from a value of .5 (see Arrington et al., 2014).

Possibly, the number of trials proposed to the participants may have played a role in the higher p(switch) observed. Indeed, due to the specificity of developmental research, a small amount of trials were used in both studies with a total of 80 trials per condition, so 160 trials per participant in Chapters 3 and 4. This strikingly contrasted with the number of trials used in adult research. Indeed, for instance, in the seminal study by Arrington and Logan (2004), participants completed 480 trials in total. In a more recent study, Mittelstädt et al. (2018) used 1008 trials. In another study exploring age-related effects on *p*(switch), Poljac et al. (2018) used 480 trials. Therefore, the number of trials used in previous VTS studies is significantly higher than in Chapters 3 and 4. Importantly, cognitive fatigue – the decrease of cognitive performance following and during the course of prolonged periods of demanding cognitive activity – has been evidenced to induce a decrease in cognitive control performance in adults Lorist, Boksem, and Ridderinkhof (2005); Lorist et al. (2000); Van der Linden, Frese, and Meijman (2003), and in children (Liu et al., 2012). Specifically, the tendency to repeat the same task more than to switch between tasks may be, among other possibilities, a way to minimize or avoid effort due to the implementation of a switching behaviour Kool et al. (2010); Westbrook et al. (2013, 2019), and this tendency could be enhanced when a large of number of trials are presented to participants. Although such a claim remains speculative, an interesting venue for future VTS research would be to test whether cognitive fatigue does impact the repetition bias in such tasks by presenting participants with a small number of trials *versus* a large number of trials. Moreover, inducing cognitive fatigue may also favour age-related differences in p(switch) between children and adults, contrary to what is observed in Chapters 3 and 4, where children show a p(switch) similar to adults. Indeed, it is plausible that children might be less resistant to cognitive fatigue than adults. Little research has investigated this question, but one study found that inducing cognitive fatigue leads to more goal neglect in an inhibitory task (Rauch & Schmitt, 2009). Younger children are particularly inclined to goal neglect (Marcovitch et al., 2010), and although this concept is separable from goal identification (Chevalier, 2015), there is reason to suspect that cognitive fatigue might affect the latter process, and perhaps even more so in children. Finally, such research would shed new lights on how cognitive fatigue affects cognitive control in children as, so far, no study has addressed this question.

3.3 Contrasting children with low and high socio-economic status and need for cross-cultural investigations

A major limitation of this dissertation is to have only tested children coming from middle to high socio-economic status (SES), which makes our samples not representative of all children. Of particular importance, school activities become increasingly self-directed with age (e.g., selecting the relevant courses to work on when preparing for an exam without clear instructions from the teacher) and engaging adaptive behaviours during these activities, and therefore engaging successful self-directed control, is likely to predict future academic achievement. Research has shown that SES is positively associated with externally-driven cognitive control, with children having the higher SES engaging more efficient cognitive control whereas children with lower SES have poorer externally-control capacities (Blakey et al., n.d.; Hackman, Gallop, Evans, & Farah, 2015; Lawson, Hook, & Farah, 2018), especially in task-switching situations from a very young age (Clearfield & Niman, 2012). As such, studying self-directed control in children with low SES should be a priority. Indeed, children with lower SES are likely to have less access to autonomous activities not supervised by adults such as reading or drawing, critical for practice of self-directed control (Barker et al., 2014), and might be engaged in more supervised activities with their siblings, as the higher SES, the fewer number of siblings (Öberg, 2017). Thus, it is possible that academic achievement is impaired, partly because of poor externally-driven control, but more critically because of self-directed control. Future studies should investigate whether and how self-directed control predicts academic achievement, and whether it does so over and beyond externally-driven control.

Further, it is important to note that our research has been conducted on children from highly educated and relatively high income and industrialised populations, also refered to as W(estern), E(ducated), I(ndustrialised), R(ich), D(emocratic) or WEIRD societies (Henrich, Heine, & Norenzayan, 2010) and comparisons between WEIRD. Whereas cognitive control performance in non-WEIRD children are absent in influential reviews (e.g., Barkley, 2012; Best & Miller, 2010; Diamond, 2013), there is a growing evidence that cognitive control and its development vary between WEIRD and non-WEIRD populations. For instance, East Asian children outperform Western children on measures of inhibition and cognitive flexibility (i.e., rule-switching flexibility; e.g., Lan, Legare, Ponitz, Li, & Morrison, 2011; Sabbagh, Xu, Carlson, Moses, & Lee, 2006). Conversely, it has been recently reported that Western children outperform African children in rule-switching flexibility Legare, Dale, Kim, and Deák (2018); Pope, Fagot, Meguerditchian, Washburn, and Hopkins (2019). However, these studies have used externally-driven tasks and the children tested had little experience with direct instructions in learning, suggesting that these effects might be essentially due to a lack of formal schooling. Interestingly, in some populations, autonomous behaviours are more prominent in childhood than in Western countries (e.g., Bushman children, see Nielsen, Tomaselli, Mushin, & Whiten, 2014). As such, it is not impossible that these children may perform better in tasks requiring children to decide on their own what to do, despite lower SES.

4 Conclusion

To conclude, here, I have attempted to investigate the underlying cognitive processes of self-directed control, a form of control which is largely under-researched in the developmental literature despite its increasing critical role in children's daily lives, and more particularly at school. One potential reason for the lack of investigations of self-directed control in children relies on the difficulty to design experimental tasks aiming to examine this form of control by providing little guidance. To overcome this difficulty, I modified the alternating-runs task-switching paradigm (Rogers & Monsell, 1995), and adapted the voluntary task-switching paradigm (Arrington & Logan, 2004) for use with children as young as 5 years-old. Doing so, I showed that goal identification is not only key in externally-driven control (e.g., Chevalier et al., 2018), but also in self-directed control and confirmed that this ability is the main source of difficulties when engaging cognitive control, especially for children (Chevalier, 2015). Critically, I claimed that goal identification and achievement is made through two key sub-processes which are context-tracking and task selection, and reported that progress in goal identification is mostly due to improvements in context-tracking rather than task selection, the latter remaining difficult in self-directed situations even during late childhood. While this confirms that self-directed control development lags behind externally-driven control development, these findings offer the first step towards a theoretical model of the underlying cognitive processes of self-directed control and their development in which future research should examine how working memory and abstract representations account for developmental progress. Finally, I hope that our results also provide key elements to encourage the elaboration of future training programmes aiming to promote autonomous behaviours during childhood.

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